ALTERNATIVES FOR CONTAINMENT OF POLLUTED GROUNDWATER, BASIN A VICINITY, ROCKY MOUNTAIN ARSENAL, DENVER, COLORADO

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This study is an engineering evaluation of alternative methods that can be employed for containing polluted groundwater in Basin A. The study utilized existing data only--no new field or laboratory testing was performed.

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Preface

This investigation was conducted during the period 24 August - 16 December 1977, by Oswald Rendon-Herrero, Consulting Engineer, Starkville, Mississippi. The study was authorized by Battelle Columbus Laboratories under a Scientific Services Agreement, Contract number DAAG29-76-D-01100. Contracting Officer's Technical Representative was Mr. D. J. Wynne, Office of Project Manager for Chemical Demilitarization, Aberdeen Proving Ground, Maryland.

This report was prepared by Oswald Rendon-Herrero. The assistance of personnel at U. S. Army Corps of Engineers, Waterways Experiment Station (WES), Engineering Studies Branch, Soil Mechanics Division, Vicksburg, Mississippi, and Rocky Mountain Arsenal, Denver, Colorado, is gratefully acknowledged.

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Introduction

Background

Rocky Mountain Arsenal (RMA), Denver, Colorado, was established in 1942 for the purpose of producing toxic chemicals and incendiary munitions. Figure 1 is a plan view of RMA. For a detailed discussion on the history (1942-1976) and mission of RMA, and for a chronology of off-post contamination, the reader is referred to a report entitled "Rocky Mountain Arsenal Off-Post Contamination Control Plan"[1]. A summary of that discussion is given in Table 1.

Between 1943 and 1957, waste products from the operations listed in Table 1 were dumped into "artificial reservoirs" that were located above the water table and separated from it by permeable sediments.[2]

The so-called artificial reservoirs were unlined and include Basin A, a 104-acre cachement area in Section 36, Reservoir B in Section 35, and Reservoirs C, D, and E in Section 26 (see Figure 2). Basin A was used as an "industrial waste basin" from 1942 through October 1955.[1] Reservoir B, C, D, and E are not known to currently be used for chemical waste disposal purposes.

In the summer of 1951, the first indication of off-post contamination occurred when some crop damage was observed on an irrigated farm northwest of RMA. In 1954 several farmers complained that groundwater,used for irrigation, had damaged their crops. ("The precipitation in 1954 was considerably below average and increased pumping from irrigation wells was required to produce crops.")[1]

Arsenal authorities first became aware of the groundwater contamination problem in 1954. In 1955 RMA took measures to halt further

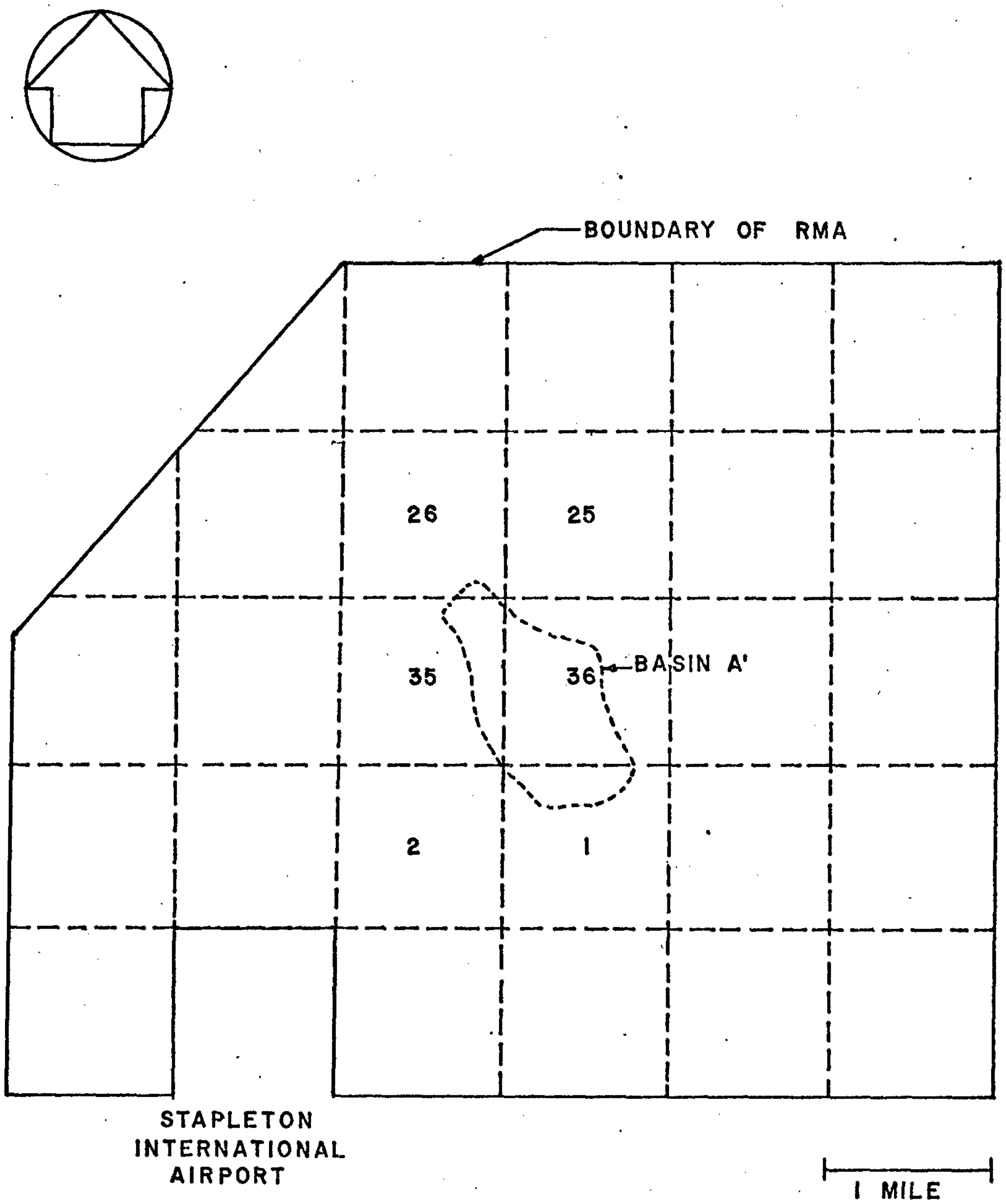


FIGURE 1: ROCKY MOUNTAIN ARSENAL, DENVER, COLORADO

Table 1 *

Operation/Production in RMA

Period	Operation/Production
1942	RMA established for production of toxic chemicals and incendiary munitions
World War II	Chemical intermediate and toxic end item products; incendiary munitions
1945-1950	Standby status. Maintenance and renovation of Chemical Corps supplies and equipment, industrial mobilization, planning, and demilitarization of obsolete hazardous and toxic munitions. Certain portions of RMA leased (c. 1946) to private industry for chemical manufacturing (insecticides, etc.).[1]
1953-1957	Manufacture of SARIN (GB) toxic chemical agent
1959-1962	Biological anti-crop agent
1965-1969	Emptying Cyanogen Chloride (CK) and Phosgene (CG) bombs for shipment
1973	Demilitarization of obsolete M34 Cluster bombs containing GB nerve gas (SARIN) stored at the Arsenal

* Summary of:

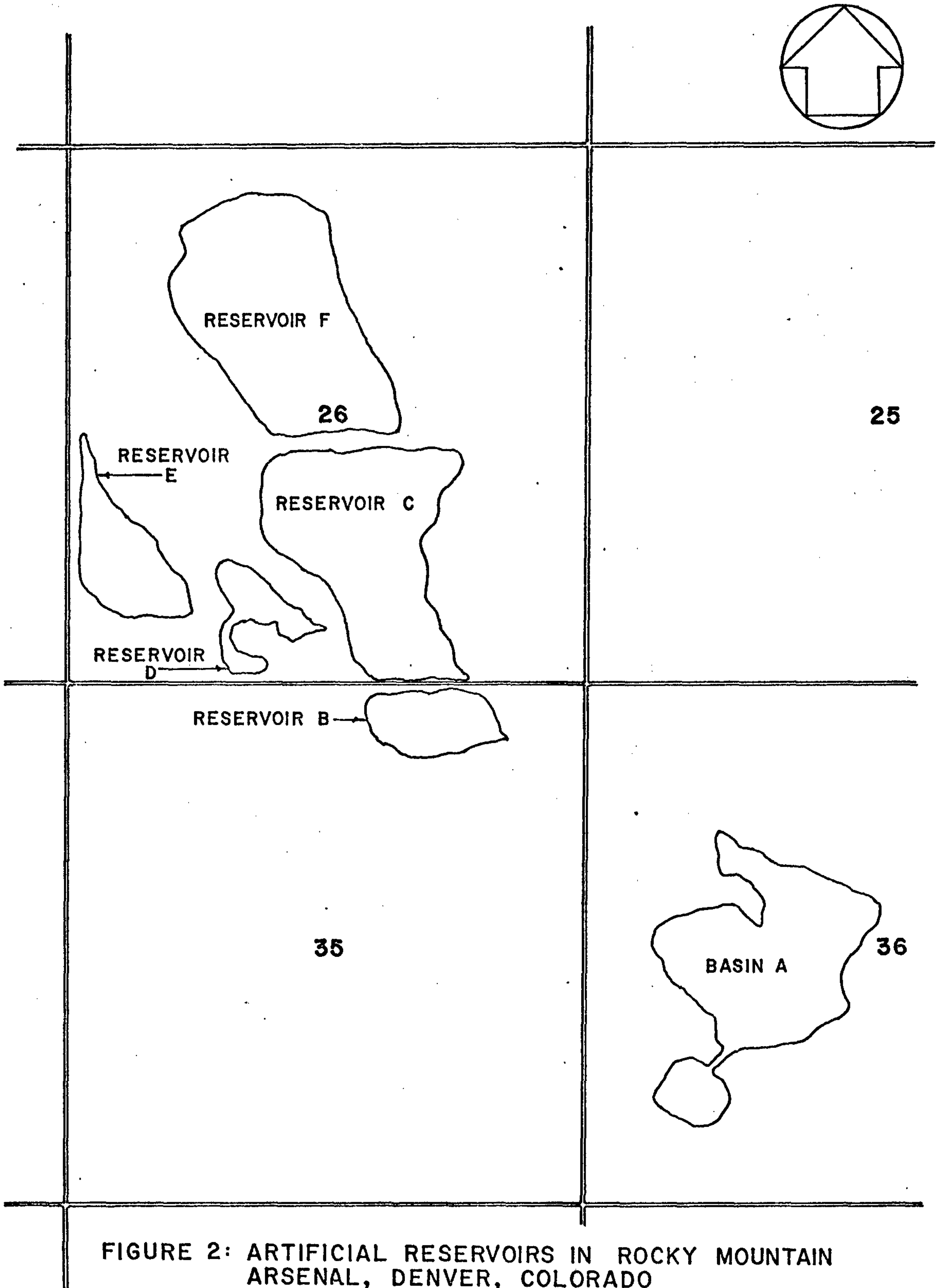


FIGURE 2: ARTIFICIAL RESERVOIRS IN ROCKY MOUNTAIN ARSENAL, DENVER, COLORADO

contamination of the groundwater aquifer. "The volume of waste produced by arsenal operations was greatly reduced, and a reservoir with an asphalt-sealed bottom was constructed in 1957 for waste disposal."[1] The asphalt-sealed reservoir is known as Reservoir F. (For a discussion of Reservoir F the reader may refer to reference 3). The use of Basin A was discontinued in 1955. DIMP, a byproduct of the chemical destruction and manufacture of GB-nerve gas, was initially disposed of in Lake A prior to 1957 and Lake F after that time.[4]

Aside from Reservoir F, most of the important sources of groundwater contamination in RMA appear to be located between two "bedrock highs" in an area that includes portions of Section 1, 2, 26, 35 and most of Section 36 (see Figure 3). For the purpose of discussion, that area is here designated Basin A'.

To prevent polluted groundwater in Basin A' from contaminating other areas in RMA and off-post, the groundwater has to be contained in-situ.

The DA Project Manager for Chemical Demilitarization and Installation Restoration (CDIR), Aberdeen Proving Ground, Maryland, requested that this consultant conduct a preliminary feasibility study (qualitative) of possible alternatives for containing polluted groundwater in Basin A'.

Purpose and Scope

This study is an engineering evaluation of alternative methods that can be employed for containing polluted groundwater in Basin A'. The study utilized existing data only--no new field or laboratory testing was performed. The scope of the study includes:

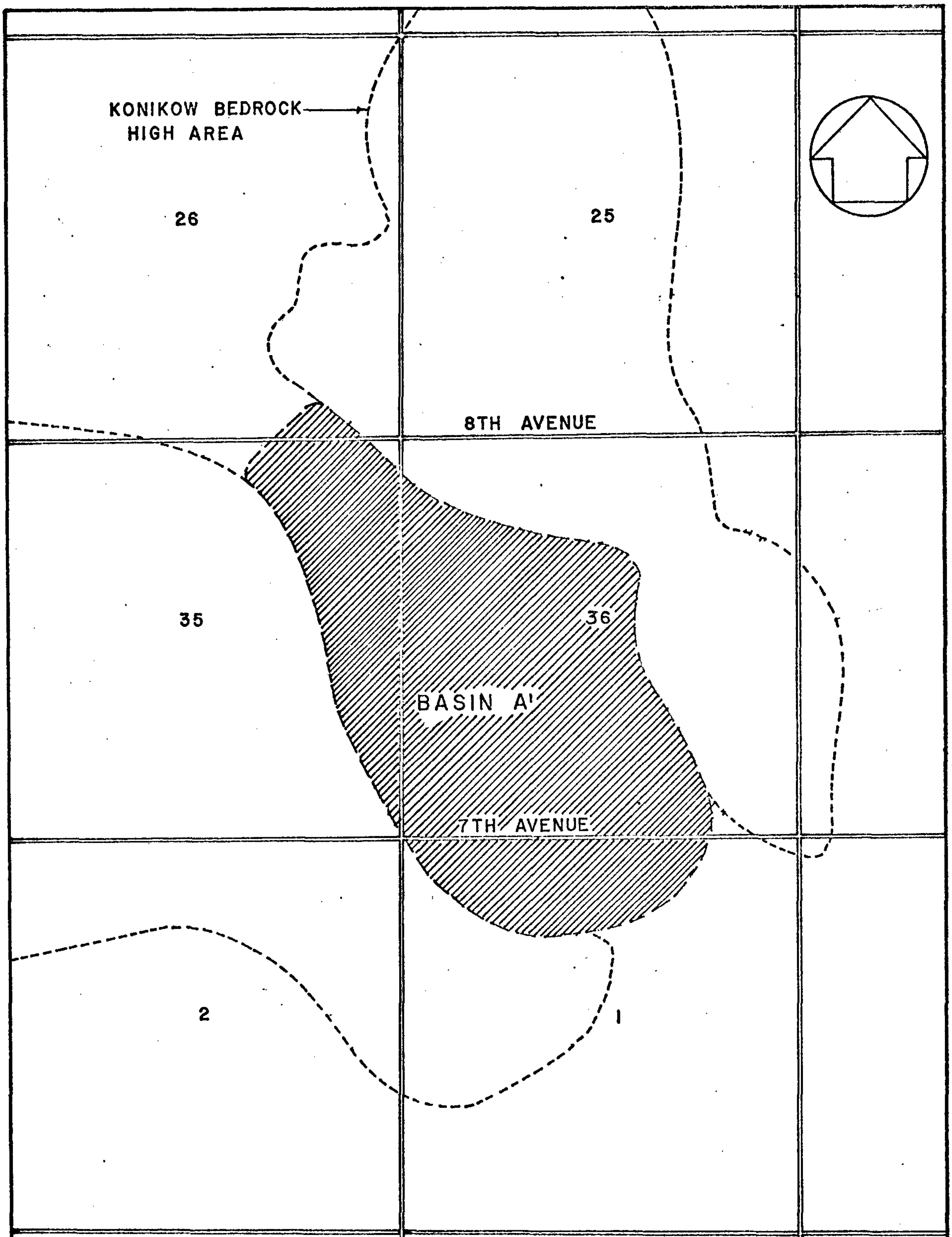


FIGURE 3: BASIN A'

a. Listing of possible alternatives (approaches, subapproaches), including description of the concept and method of implementation.

b. Listing and discussion of the types of studies required for a detailed quantitative feasibility evaluation of the possible alternatives.

c. Preliminary qualitative feasibility evaluation of subapproaches, discussing the rationale for deleting certain methods, and estimates of cost and time schedules for determining detailed quantitative feasibility and accomplishment (design, construction, etc.) for methods retained for consideration.

d. Final qualitative evaluation for selecting methods to be studied in more detail.

e. Preparation of a final report for filing with the Program Manager, CDIR, by December 16, 1977.

Appendix A, is a copy of the original directive from the Program Manager, CDIR, which describes the scope of the work.

Constraints

The following are the imposed and self-imposed constraints under which the study was performed. (A physical model of Basin A' - characteristics, response, etc. - is given in "Proposed Physical Model of Basin A'", of this report):

a. Consider the most feasible methods from a qualitative standpoint only.

b. The dimensions of Basin A' are the peripheral limits as described in the Statement of Work (TCN:77-363 and Figure A1) Appendix A, and vertically down to unpermeable bedrock.

c. Groundwater movements and/or contamination migration are not to be considered.

d. After implementation of the selected method, no further discharge of contaminants will be made into the basin.

e. Prepare a verbal presentation on November 1977 (date to be set by PMO), and submita written report on December 16, 1977.

Study Area (Basin A')

The elliptically-shaped area subject of this report is here designated as Basin A' and is shown on Figure 3. A large portion of Basin A' is located in Section 36 between two so-called bedrock highs. (The term "bedrock high" is attributed to Konikow[5], and is defined as an area where the alluvium is absent or unsaturated)[1]. Basin A' is approximately 1.0-mile square in area (551.0 acres) and also emcompasses portions of Section 1, 26, and 35. It is possible that the limits of Basin A' shown on Figure 3 also define the approximate boundary of a groundwater catchment area.

Shown on Figure 4 are a number of areas located in Basin A, that are thought or reported to be significant sources of groundwater pollution. The areas are listed on Table 2.

The current general concensus concerning degree of contamination by source areas appears to be that the locations contributing the greatest amount of groundwater contamination in Basin A' include the southwest corner of Section 36 (i.e., the contaminated and utility sewer lines, lime settling basins, influent discharge point to Basin A , and the drain field) and the Plants area in Section 1 and 2. Although Basin A is reported to be an important source of groundwater contamination, it does not appear to be as serious a contributor as the aforementioned area in the southwest corner of Basin A'.[7]

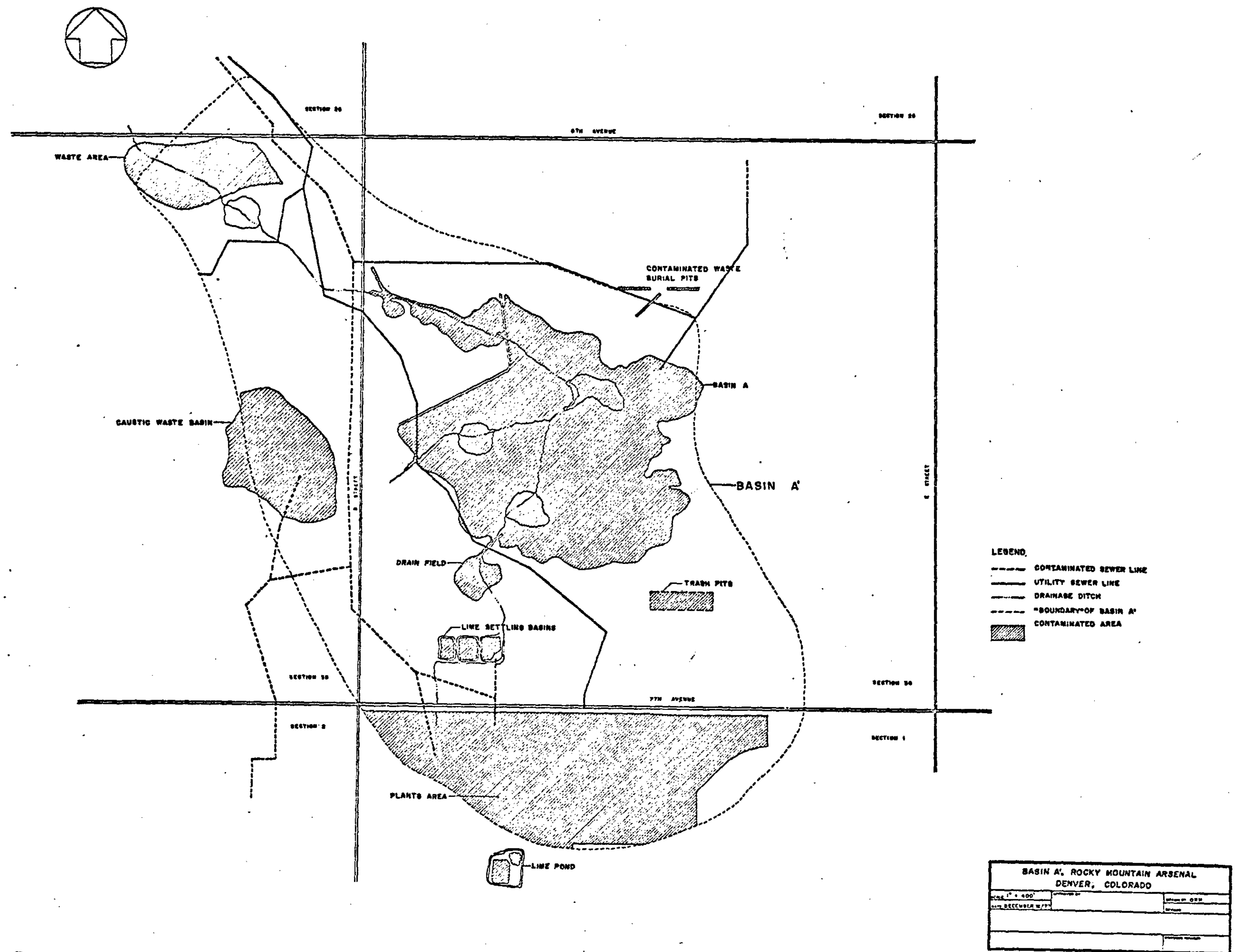


FIGURE 4 : LOCATION OF POSSIBLE/KNOWN SOURCES OF GROUNDWATER POLLUTION IN BASIN A'

Table 2

Possible/Known Sources of Groundwater Contamination in Basin A[e]

Map Section Location	Source	Comment
1	lime pond (2.4 acres)[f].	It is not known if the bed of the pond is lined.
1	plants area (75.0 acres[g]).	Runoff and infiltration, and disposal to sewer lines is unknown.
1,35,36,26	contaminated sewer line.	
1[a],36[b,c],35[d],26	utility sewer line.	
36	lime settling basins (3.4 acres).	
36	influent chemical waste discharge point.	influent to Basin A
36	drain field (boundary of the area is unknown).	
36	trash pits (2.3 acres).	
36	Basin A (104.0 acres).	According to available information, boundary of Basin A is contour 5240. ft. msl.
35	caustic waste basin (20.5 acres)	
36,35	storm runoff drainage ditch	
36	contaminated waste burial pits (about 0.6 acres)	
35	waste area (15.1 acres)	

Table 2

Continued

Map Section Location	Source	Comment
-	other	Some pipelines of unknown origin were observed to be discharging into ditches, etc., during field inspection.[6] These are not shown on any drawings, etc.

a. Information obtained during conversations with RMA personnel in September 1977[6], suggests that on a number of occasions (emergencies, etc.) the utility sewer lines have been used for disposal of chemical wastes.

b. Source also from "GB-Complex" (located in Section 25).

c. There is an indication that a contaminated waste sewer line may have been connected (date unknown) directly to a utility sewer line at the GB-Complex area.

d. Source also from Warehouse area (located in Section 3 and 4).

e. The sources are listed as they appear in Basin A' from south to north. No attempt is made to rank the sources according to degree and/or quantity of contamination.

f. Areas indicated in parenthesis are approximate (determined by planimeter).

g. Plants area enclosed with Basin A'.

Site Conditions

Overburden

About 90 test borings have been performed in Basin A' (see Figure 5). The distance between borings averages about 300 feet. A series of test borings (Kal Zeff) were made to a relatively shallow depth (4 to 6 feet) beneath the ground surface. (Some of the shallow test borings were primarily made for the purpose of evaluating the chemical contamination of the surficial soils in certain areas of Basin A', whereas the remaining borings were drilled deeper to an apparent bedrock surface). Information on the condition and properties of the bedrock in Basin A' is not currently available. However, some indications are that most of the so-called bedrock appears to be in a weathered condition to a depth of several feet. (Further reference to the bedrock in this report will omit the use of the adjective "apparent"). The thickness of the overburden in Basin A, disclosed by test borings, varies between 13.5 to 40.6 feet and averages 26.0 feet. Around the northeast and southeast boundary of Basin A', the thickness of the overburden averages 13.0 feet. Little is known concerning the overburden and subsurface conditions on the southwest and west boundary of Basin A'.

Generally, the quality of the geotechnical information given on the available test boring logs is considered to be fair to poor. (Sands, e.g., are described as being soft; however, soft is a term used to qualitatively describe a particular consistency state of clay soil materials). A similar assessment about the quality of geotechnical information was

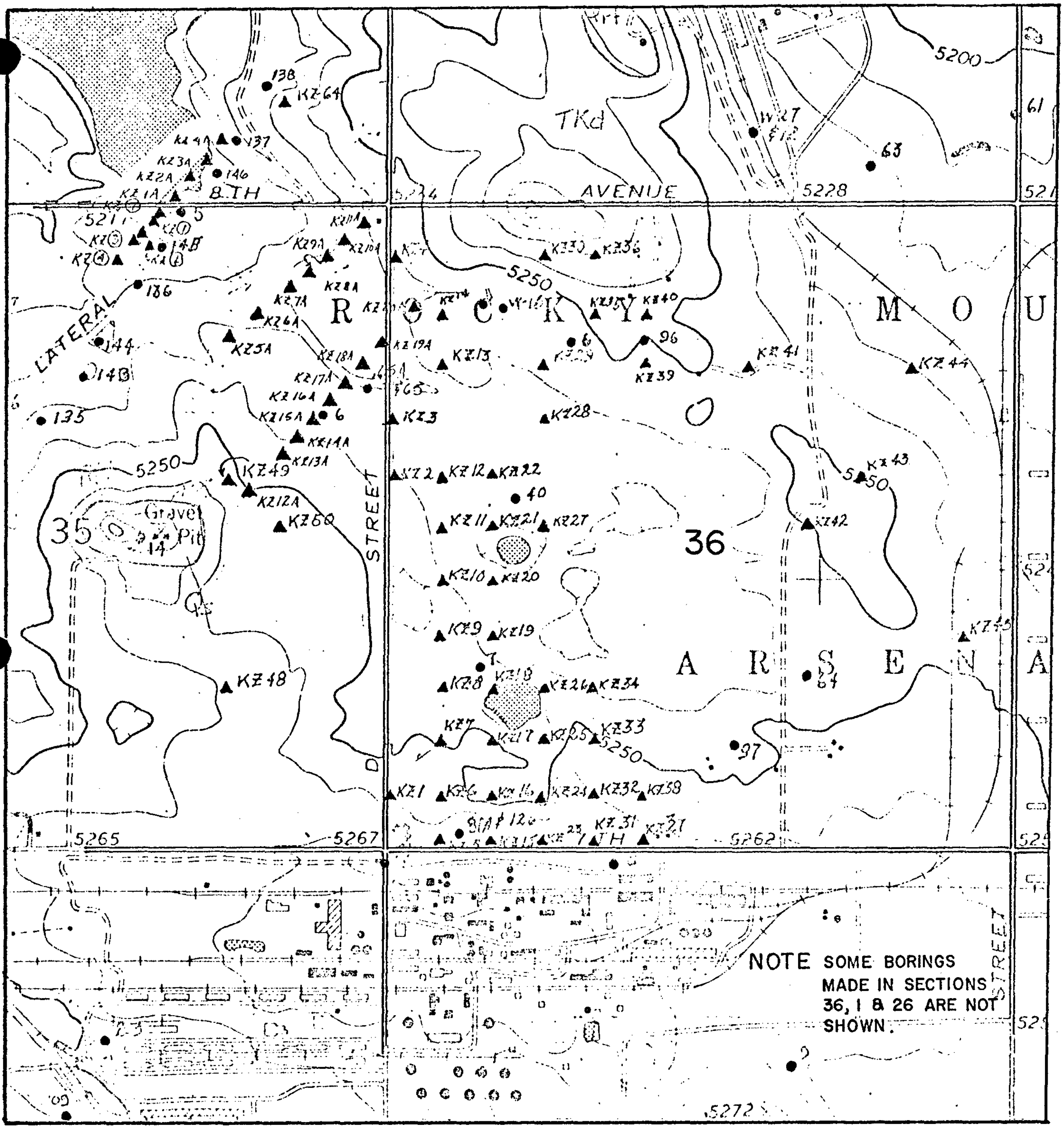


FIGURE 5: LOCATION OF TEST BORINGS IN/NEAR BASIN A'

given in a 1961 Corps report, apparently relating to the "deep" borings. It was stated in the report that late in the period of that particular study,"the Omaha District was advised that the results of soils analysis in the Reservoir A area are erroneous because of improper laboratory procedures".[7] (No indication is given on that report as to what is meant by "soil analysis"). A review of the soil descriptions given on most of the available logs for test borings performed in and near Basin A', indicates that they may not be consistent. That is, soil descriptions given by different loggers for apparently the same soil materials, seem to vary considerably. In some cases the soil descriptions do not even appear to be accurate. Because of the relatively large distances that exist between some test borings, it is also difficult to extrapolate soil conditions between individual test borings. It is therefore not feasible with the available information, to construct soil profiles which can be considered to be representative of the subsoil conditions existing in and around Basin A'. Otherwise, information obtained from the test borings concerning the depth to the groundwater table, thickness of the overburden, or the depth to bedrock, however, is generally useful.

Most of the shallow test borings performed in Basin A' describe the soil profile to an average depth of 5.0 feet below the ground surface. Because of a considerable lack of information on the test boring logs (deep borings), it is also difficult to assess the relative density/consistency condition of the subsoil materials. Where information concerning the number of blows required to "drive a sample barrel of the diameter indicated" is given, it is not possible for one to estimate the relative density/consistency condition of the subsoil. This is mainly because both the weight and fall of the drive

hammer were varied between test boring locations. In any event, penetration resistance-relative density/consistency correlations are not known to exist for such sampling procedures. The lack of information on the relative density/consistency condition of the subsoil, therefore, makes a comparison of the subsoils based on sampler driving resistance unfeasible. For the reasons given, a characterization of the subsoil's relative density/consistency condition in Basin A' will not be included in this report.

Healy, et al[8], reported that the overburden (0 to 30 feet in thickness) in the upland area east of the South Platte River generally consists of eolian sands of "early Recent age". They have also indicated that the bedrock" is covered in many places by unconsolidated surficial deposits of silt, sand, and gravel of pleistocene and recent age". In a 1961 Corps report, the origin of the overburden soils in RMA are said to arise as the result of erosion of coarse sediments (Monument Greek group: Castle Rock Conglomerate-Oligocene and Dawson Arkose - Denver and Arapahoe formations) and the underlying Laramie formation. The fine to medium sand is also reported to consist of fairly large amounts of silt and silty sand. Reporting on the overburden conditions on and near the northern boundary of RMA, Miller[9] stated that the soils are generally "lean clays (CL) overlying sands (SC,SP)..." Concerning the overburden in and near Reservoir F, this writer concluded that the surficial layer consists of clayey or silty sands underlain by a layer of coarse sands, gravel, and occasional cobbles.[3] The overburden in the southeast part of RMA is reported to consist primarily of fine sediments of silty, clayey, fine sands and fine sandy silts.[7] According to Kolmer,[10] the sediment above the bedrock

in Basin A' is a "clayey silty sand. At times, some lenses of clean sand were encountered but these units were not extensive."[10]

For the reasons given previously in this report, it is difficult to construct a model of the overburden soils that can be considered to be representative of Basin A'. Based on the available information for Basin A', however, it can be said that generally the overburden consists of strata of sand having a low permeability due to the presence of fines in varying proportions. The following model of the overburden in Basin A' is proposed: The surficial soil is a layer (about 10 feet) of fine to medium sand with little to some silt and/or clay; (some borings indicate that the surficial soil is a clay, or clay and sand). The underlying soil strata to bedrock consists of mixtures of sand, clay, and/or silt. Individual strata and lense thicknesses vary approximately between a few inches to 10 feet. Occasional clean sand lenses are encountered throughout the depth of the overburden. The lack of materials like coarse sand, gravel, and cobbles is notable. This is because the "alluvial gravels and gravelly sands that lie on bedrock pinch out against the rising bedrock surface in the southeast section of the area."[7] (Soils encountered directly above the bedrock in parts of Section 26, contained appreciable amounts of gravel, gravelly sands, and occasional cobbles.)

Although the water table measurements that were made in Basin A' appear to be consistent, it is to be noted that water table observations that are made in deposits of soil having a low permeability, need to be made over an extended period of time to allow the water in the test hole to reach an equilibrium level; since the overburden in

Basin A' contains fine-grain soils in varying proportions, long-term water table observations are required. A review of water table observations made in Basin A' indicates that they were relatively short-term (ie., made during the duration of the drilling operations). The reported water table depth averaged 5.5 feet in Basin A, and 6.0 feet in Basin A' (Water table observations that were made near the boundary of Basin A' corroborate the Konikow "bedrock high" areas with a few exceptions. These exceptions are discussed in a subsequent section of this report.)

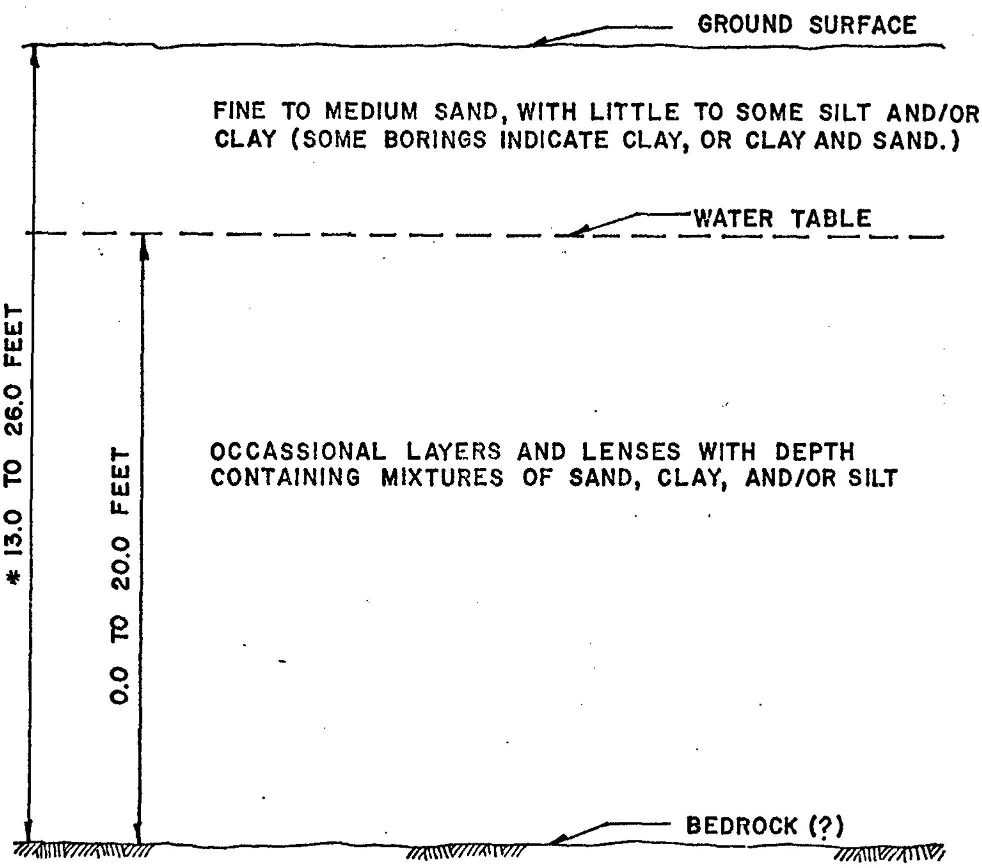
RMA personnel have indicated[11] that the surficial soil in Basin A' and vicinity has been excavated and backfilled on numerous occasions. The extent or depth of these operations is unknown.

Figure 6 is an idealized soil profile for the overburden in Basin A'.

Geology

RMA is located on the High Plains of Colorado about 20 miles east of the Front range of the Central Rocky Mountains. According to Healy , et al [8], the area lies in the Colorado Piedmont section of the Great Plains physiographic province and is underlain by 12,000 feet of sedimentary rocks ranging in age from Paleozoic to Cenozoic. Denver and RMA are located "over the deepest part of the north-trending asymmetrical Denver basin".

Appendix B, is a tabulation[12] of geologic stratigraphy based on four wells drilled in the vicinity of Reservoir F (reproduced from reference 31.)



* OTHER DESCRIPTIONS GIVEN FOR OVERBURDEN IN BASIN A'
1. SILTY CLAYEY FINE SANDS AND FINE SANDY SILTS (REF. 7)
2. CLAYEY SILTY SAND WITH OCCASIONAL CLEAN SAND LENSES (REF. 10)

FIGURE 6 : IDEALIZED SOIL PROFILE

Bedrock

A discussion of the historical geology and the bedrock in RMA is given in a Corps of Engineers report, "Program for Reclamation of Surface Aquifer, Rocky Mountain Arsenal" dated 1961.[7] The report describes the bedrock as belonging to the Laramie formation and consisting of poorly indurated gray, silty and sandy clay and brown to gray silty, clayey fine sand that is generally impervious. Concerning the bedrock near the northern boundary, Miller reports that the bedrock is a weathered shale (usually a fat clay CH or an inorganic silt MH) or weathered sandstone (usually lean clay and silty sand CL-SM or silty sand SM) above the unweathered bedrock.[9] Kolmer[10] describes the bedrock in Basin A' as generally composed of clay/claystone with some sand/sandstone. Extreme bedrock surface elevations measured in Basin A' are 5125 and 5247 ft msl, at Borings number 96 and 81, respectively.

The Laramie formation is said to "outcrop" at three localities in RMA.[7] The exposures are located east and north of Basin A' in Sections 25, 35, and 36, T2S, R67W, and are characterized by prominent topographic highs.[7]

According to Healy, et al,[8] no faults are known to exist in the bedrock in an area 10 miles around and including Basin A. If the unweathered bedrock is impervious and relatively sound therefore, all groundwater in Basin A' will flow laterally in a northwesterly direction.

Bedrock-Surface Erosional Features

Streams are reported[7] to have formed an erosional surface on the Laramie formation during Quarternary time and covered it with alluvial terrace and channel deposits. The bedrock erosional surface in RMA is also reported to slope from the southeast to northwest and is "cut by numerous buried channels and gullies".[7]

Basin A' is underlain by a subsurface drainage system located between two "bedrock highs" that collect and transmit groundwater in a general northwesterly direction to the South Platte River. Schwochow has described[13] the channel as the "approximate boundaries of ancient Cherry Creek tributary valley". A number of borings (11, 40, 63, 65, 65A, DH-138 and DH-146) appear to corroborate the existence of the channel. The groundwater drainage system is here thought to consist of three interconnected bedrock - surface erosional features; (1) a channel flowing from the Plants area (Sections 1 and 2) to Basin A, (2) a "bowl"-shaped depression (bedrock cachement) under Basin A, and (3) a channel flowing from Basin A in a northwesterly direction toward Reservoir F. ("A buried channel sloping northwest appears to originate beneath Reservoir A and trends northwest between two bedrock highs in Sections 25 and 35, T25, R67W, then swings west, due south of Reservoir F, to the west boundary of the Arsenal at which point it swings north and northwest; (this channel is located in Sections 21, 22, 26, 27, 35, and 36, T25, R67W)")[7]. The channel is "V"-shaped at the point where it emerges from Basin A and flattens out as it crosses Section 34 toward the northwest.[10] Subsurface drainage in the report area is controlled by the impervious bedrock erosional surface".[7]

For the purpose of discussion, the three bedrock-surface erosional features are here designated as bedrock channel "a_i", bedrock cachement area "a", and bedrock channel "a_o", respectively. (The subscripts "i" and "o" designate the direction of groundwater flow relative to cachement area "a", ie., in and out, respectively).

Figure 7 is a schematic drawing that shows the approximate location of the aforementioned bedrock-surface erosional features under Basin A'.

The existence of channel "a_i" is suggested in a number of reports (e.g., 7, 10, 14). Trost points out that the existence of a Quarternary alluvium exceeding 30 feet in some areas (e.g., the Plants area) in RMA," significantly modifies Konikow's bedrock - high areas and explains the presence of anomalous DIMP concentrations in Konikow's areas of bedrock-highs".[14] According to Kolmer[10], there is some indication (e.g., Boring number 21 and 22[10]) that infiltration from Upper Derby Lake may be providing a good portion of the groundwater recharge under Basin A'.

Another bedrock channel appears to exist east of Basin A'.[10] The channel slopes south to north approximately following First Creek. The channel does not appear to be connected to the a_i-a_o groundwater drainage system in Basin A'.

Groundwater

Relatively little water was encountered in test borings performed along the east and southeast boundary of Basin A'.[10] A phreatic surface was encountered along the southwest boundary of Basin A' under the Plants area.[10] Little is known about the subsurface conditions along the middle and lower southwest portion of Basin A'; indications are, however (ie., according to Konikow, etc.), that a water table as such does not exist in this area.

In general, the overburden thickens from the boundary of Basin A' toward its "center" (ie., from about 13.0 to about 26.0 feet, respectively), suggesting that the bedrock surface in Basin A' is a groundwater cachement area.

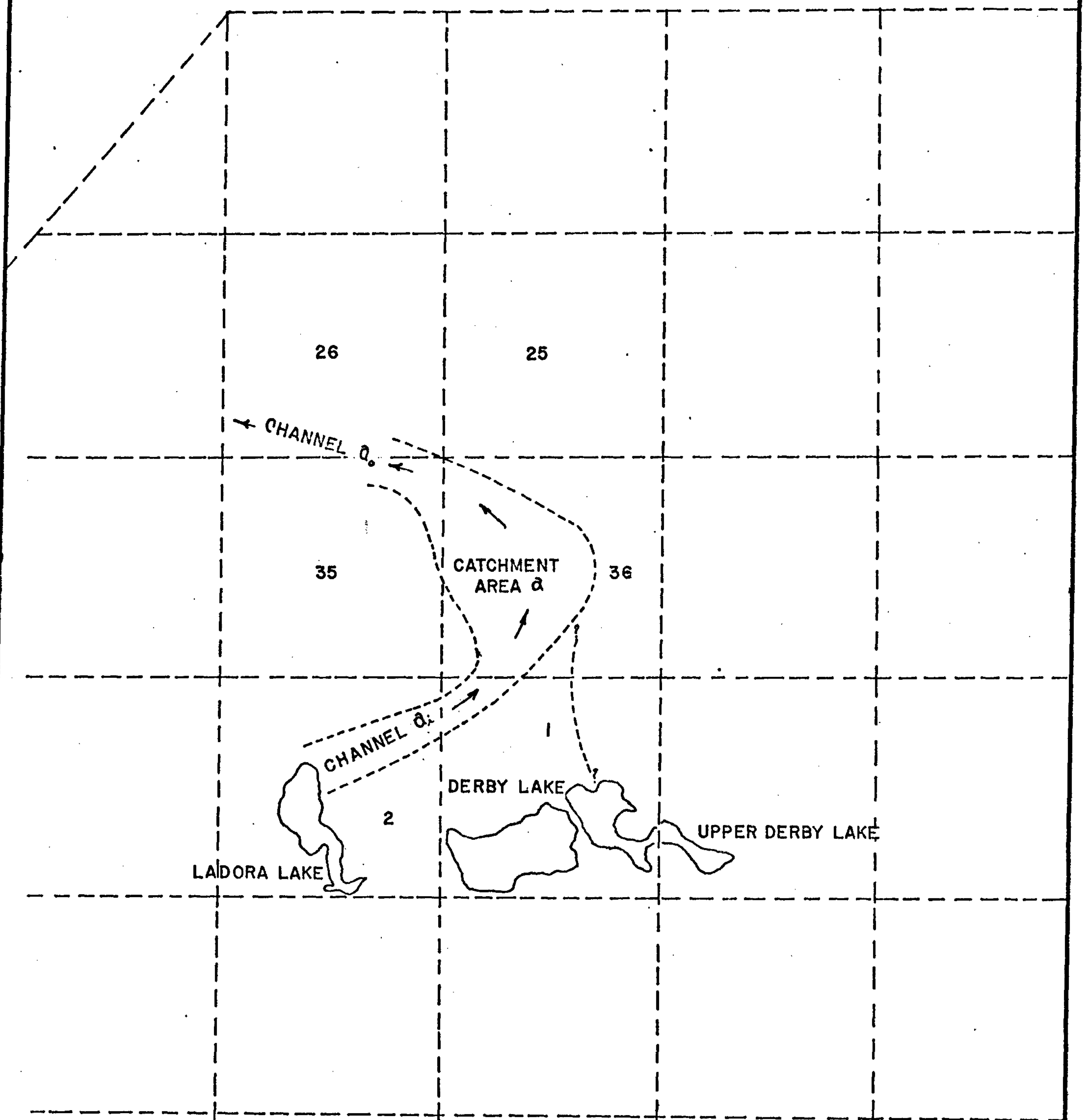


FIGURE 7: BEDROCK SURFACE EROSIONAL FEATURES IN BASIN A'
(BEDROCK CHANNEL a_i AND a_o, AND CATCHMENT a) — SCHEMATIC

The average depth of the groundwater table in Basin A' is on the order of 6 feet. Near the boundary of Basin A' the depth of the water table averages 0.0 feet; in the interior of Basin A', the water table has been observed at depths from the ground surface varying between 3.0 and 13.0 feet. The groundwater table has been reported to be relatively stable with only very minor seasonal variations.[7] The groundwater gradient is said to average about 40 feet per mile in RMA. In Basin A', the groundwater gradient appears to be less than in other areas of RMA, and averages about 29 feet per mile.

The source of the groundwater in Basin A' is from infiltration as the result of precipitation (rainfall and snowmelt) and seepage from the lakes located south of Basin A'.

Groundwater Recharge

Groundwater recharge in Basin A' appears to result from two sources, infiltration from rainfall and snowmelt, and subsurface seepage from the lake area south of the basin. Seepage from other areas (east and northeast of Basin A') is also suspected; however, the amount of recharge is thought to be relatively minor. It is reported that the groundwater in RMA is generally recharged from the south and east.[7] Kolmer states that there is some indication that seepage from Upper Derby Lake may be providing a good portion of the groundwater recharge under Basin A'.[10]

The annual average precipitation in RMA (U.S. Weather Bureau) is about 14 inches. The surface runoff in RMA is unknown, but is probably low due to the "irregular topography and relatively high permeability of much of the surficial material".[7] That is, the area probably receives an above-average percentage of recharge from precipitation.[7]

Idealized Groundwater Flow in Basin A'

According to an evaluation of the available information on the overburden, groundwater, bedrock, and chemical contamination, Basin A' appears to be underlain by a groundwater drainage system that directs the flow from the Plants area (and possibly the lakes south of the Plants area) to Basin A, where it turns and heads in a northwesterly direction to a point southwest of Reservoir F.[1,10,15] From that point the flow continues on a west-northwest course to the South Platte River. The approximate path of the groundwater flow is indicated on Figure 7. In any event the general direction of groundwater flow is from "regions of higher water table altitudes to lower water table altitudes and approximately perpendicular to the water table contours".[1] According to USGS mathematical hydrological models, geotechnical, and geochemical data from RMA, and off-post observation wells, the flow of groundwater in RMA is "essentially south to north".[15] The configuration of the water table indicates that the groundwater "Immigrates beneath the Arsenal waste basins in a generally northwest direction toward the South Platte River Valley".[1]

The lateral limits of groundwater contamination is said to be essentially dependent upon groundwater flow with very little lateral dispersion.[7]

Groundwater Contamination

Based on available bedrock and groundwater contour maps, groundwater contaminants that originate in Basin A', are thought to flow in a northwesterly direction from the basin. ("As a result of the unique position occupied by Reservoir A, the aquifer in the buried channel beneath the reservoir contains and transmits any contaminated water

which may seep from Reservoir A".[7] Another report[1] states, "Basin A and a possible leak in the chemical waste sewer line at Reservoir F are the probable sources of contamination in the alluvial aquifer". Concerning the "possible leak", it is reported[7] that "... a loss of flow of 11.1 percent was discovered in the waste pipeline from the plant areas to Reservoir F. This resulted in an average loss of flow to the aquifer of 14.5 gallons per minute. Although this is a relatively small quantity, the concentration is adequate to result in the addition of considerable contaminant to the aquifer".[7] Another possible but less likely source is one of the two small diked areas southeast of Reservoir F.[1] When the contaminated groundwater reaches Section 26 south of Reservoir F, it then travels due west to Section 27 where it turns due north through Section 22 through the northwest boundary of RMA.

Studies conducted by the USGS and the University of Colorado "indicate that the primary contaminants were sodium and chlorides and that these contaminants were carried off-post by underground water which travelled in a northwesterly direction".[1]

There is some indication that some of the contaminated groundwater flow which emerges from Basin A' through Section 35, is diverted in a northerly direction in the vicinity of the southeast corner of Section 26.[5,16] From that point, the contaminated groundwater is said to flow in a general northerly direction to the north boundary of RMA. Based on conversations with RMA personnel, the flow of polluted groundwater from Section 35 in a direction east of Reservoir F is thought to be highly unlikely.[6] (The flow of contaminated groundwater originating

from Basin F is discussed in a number of publications (e.g., 1,3,5,14,17). There is some indication that there are two probable sources of groundwater contamination at Reservoir F: (1) leakage through asphalt membrane (seal), and (2) leakage of the chemical waste sewer line feeding into Reservoir F.[1])

Basin A appears to be a major source of chloride groundwater contamination. Based on geochemical dispersion maps and correlation coefficients "it appears that DIMP/Cl are dispersing northward from Basin A area probably along a bedrock channel. Endrin, dieldrin and DCPD, however, have a source along the east side of Reservoir F.... Some minor source of endrin and DCPD may also be present in Reservoir A area".[14] Shukle reported, however, that Basin A "is a very doubtful source for the aldrin and endrin found in wells in the southeast corner of Reservoir F."[4] Shukle also supports the view that Basin A is a source of DIMP.[4] According to Trost, Basin A is a source of sulphate but that it is rapidly diluted towards the north.[17]

An isochlor map of RMA indicates that the highest concentration of chloride (5000 ppm) was observed on the northwesternmost part of Basin A .[7] (Some chloride groundwater contamination also appears to be coming from the Plants area south of Basin A in Section 2 and 1[7]). This idea is supported by a 1961 Corps of Engineers report stating that "in view of the 'finger' of rather highly contaminated water that extends under Reservoir A to the southwest for approximately one mile, it is considered that continued <u>pollution from an unknown source within the industrial area is perhaps of greater significance than possible leaching of Reservoir A.</u>"[7] (Underlined by the writer). The report

(ie., reference number 7) goes on to state, "... considerable leakage has been observed from surface lines in the plant areas. Such leakage probably contributes considerably to the contamination of the aquifer and is undoubtedly the cause of the high contamination in the aquifer underlying the plant area..." Recent discussions with RMA personnel support the idea that the discharge area in the southwest corner of Section 36 is considerably more contaminated than most of the other probable pollution sources in RMA.[6]

Contaminated Overburden

Chemical waste disposal was conducted in Basin A from 1942 until 1955 by discharging directly on the surficial soil in the basin. . .[6] that is, without the benefit of treatment or lining the soil. The chemical wastes deposited include large quantities of organophosphates, chlorinated hydrocarbons, and other chemical waste materials (World War II - 1955).[1]

Because it has generally been thought that Basin A is a major source of groundwater pollution in RMA, studies of soil contamination have been concentrated in that particular area. (Another area where soil samples were taken for chemical contamination studies, is located in the southwest corner of Section 36). The location of bed-sampling points (16 drill holes) in Basin A and the results of tests to determine the degree of soil contamination by chloride, fluoride, and arsenic in ppm, is reproduced from a Corps report[7] and shown in Figure C1, Appendix C.

The preliminary investigation indicated that the contaminated soil materials in the bed of the basin are not contributing to the polluted aquifer to a sufficient degree to warrant remedial measures. It is

also considered that increased infiltration resulting from ponding of water in Basin A would not result in a detrimental increase in contamination of the aquifer.[7] "The preliminary analysis indicated that the degree of contamination of the reservoir bed materials was not appreciably greater than that of the contaminated aquifer. There was also a general indication that the degree of contamination decreases with depth".[7] The degree and depth of contamination of the soil lying directly beneath the source areas, that are listed on Table 2, are currently unknown. This statement may also apply to the other areas in Basin A' that are not listed in Table 2. It is felt, however, that the degree and extent of contamination in these areas are negligible.

Contaminated waste materials have been buried in Section 36 in two known locations (see Figure 4). One location consists of three pits containing contaminated metals such as pipes, valves, vessels, etc.; also filter-cake and insoluble-still bottoms from the Shell plant. The depth of burial is reported to vary from 0 to 15 feet. One reference indicates that the waste materials in the burial pits will not appreciably add to the contamination of the groundwater.[7] Little is known concerning overburden contamination at the "Trash Pit" waste burial area that is located near the southeast corner of Basin A.

Previously Suggested Methods for Containment of Groundwater in Basin A'

A few methods have been proposed to prevent runoff from infiltrating the ground surface and leaching contaminants from the soil in Basin A'. These methods consist of grading and contouring of the ground surface, and the construction of ditches to allow for the immediate runoff, collection and transport of surface waters.[1] Also proposed was the construction of an underground "bentonite dam" in Section 35 across channel a_o.[1] Based on this proposal, the "impounded" ground water upstream of the dam would be pumped into the chemical sewer line leading to Reservoir F by a system of four wells. This particular proposal, however, is not feasible as all of the current chemical waste disposal into Reservoir F has or will be discontinued in the near future.

According to Kolmer[10], recharge of the groundwater aquifer in Basin A' derives from two sources: infiltration from rainfall and snowmelt, and seepage from Upper Derby Lake south of the Plants area. Kolmer suggests that the groundwater contribution from seepage can be reduced by lowering the level of the lake.

Proposed Physical Model of Basin A'

Based on a review of available information, the following physical model of Basin A' is proposed:

1. The groundwater and bedrock surfaces in Basin A' are catchment areas for precipitation and groundwater seepage, respectively. The actual ground and bedrock surface catchment boundary (divide) extends beyond the limits shown for Basin A'.
2. Water from surface runoff, infiltration from precipitation, and groundwater seepage, are collected and transmitted in a northwesterly direction from Basin A', by surface ditches and overland as runoff, and by bedrock surface erosional features, respectively. The bedrock surface erosional features consist of channel a_i, catchment area "a" and channel a_o (see Figure 7).
3. Groundwater recharge is derived from infiltration and seepage from Upper Derby Lake. (The relative amount contributed by infiltration and seepage is unknown.)
4. Overburden consists of silty and/or clayey sands. Layers and pockets consisting of mixtures of other soils are often encountered throughout the strata. The overburden is relatively impervious. Figure 6 is an idealized soil profile for the overburden in Basin A'.
5. The overburden is thinnest (about 16 feet) along the boundary of Basin A', and thickens (about 26 feet) toward the center of the basin (approximately at the center of Basin A.
6. The zone of saturation (groundwater aquifer) beneath the ground surface is thinnest (about 0 feet) along the boundary of Basin A'; toward the center of the Basin it begins to thicken to about 20 feet.

7. Areas in Basin A' where the overburden is suspected and/or known to be contaminated are listed on Table 2.

8. Areas contributing the greatest amount of groundwater pollution in Basin A' include the southwest corner of Section 36, the Plants area, and Basin A. (The degree to which other areas in Basin A' that are listed on Table 2 contribute to groundwater pollution is unknown.)

9. The degree of contamination of the surficial soil in the source areas listed on Table 2 is not appreciably greater than that of the soil in the contaminated aquifer.

10. Contamination of the overburden in areas that are not listed on Table 2 (that is non-source areas), is negligible.

11. Since after implementation of a selected method for containing polluted groundwater, no further discharge of contaminants will be made into Basin A' (similar plans are being proposed for Reservoir F[3]), there will not be any further need for the contaminated sewer and utility lines. A consideration of the eventual relocation site for the lines is not within the scope of this report.

12. Groundwater pollution results from the detachment and transport (ie., leaching) of chemical deposits that are adsorbed to or lodged between soil particles by infiltration and seepage, and percolation from surface storage and/or leaks.

13. Flow of contaminated groundwater in Basin A', is from channel a_i, through catchment area "a", and out through channel a_o.

Alternatives for Containment of Groundwater in Basin A'

Most, if not all of the contaminated groundwater in, or passing through Basin A', migrates to other areas in RMA via bedrock channel a_o. To reduce or inhibit the amount of "downstream" groundwater pollution resulting from (1) chemical soil leaching by infiltration and groundwater flow, and (2) from percolation of chemicals from surface storage and/or "leaks" in Basin A', the contaminants must be detained in the basin by some means.

Curtailment of infiltration to reduce groundwater pollution can be accomplished by sealing the ground surface and/or by increasing the amount of overland runoff. The amount of overland runoff can be increased by improving surface drainage (ie., via contouring and grading, and construction of surface runoff collection ditches).

Groundwater transport of contaminants to areas outside of Basin A' can be curtailed by reducing or inhibiting the amount of groundwater flow, or by containing or relocating source areas of pollution to other locations within the basin. Curtailment of surface leaks can be accomplished by the removal and relocation of sewer and utility lines. (There is some question as to whether the sewer and utility lines that currently serve the Plants and other areas, will continue to be used in light of current proposals to discontinue use of Basin A' and Reservoir F (re: Constraints, reference number 3) as chemical waste disposal basins. Relocation of the sewer and utility lines will, therefore, depend on the future site in RMA for the eventual disposal of chemical wastes produced in the Plants and other chemical

manufacturing areas in RMA. Such a consideration, that of the eventual relocation site for sewer and utility lines in Basin A', is outside the scope of this report.)

Curtailment of surface "spills" and "leaks" in the Plants and other areas will also require the development and implementation of a formal policy between RMA and the current leaseholders.

Containment of polluted groundwater in Basin A' can be accomplished by a combination of some or all of the above described methods (ie., methods to reduce infiltration and flow of polluted groundwaters). The number of possible combinations is appreciable. A consideration in this study of all the possible combinations is not currently justified because of the lack of detailed information concerning Basin A' (e.g., bedrock surface topography, bedrock erosional surface features, overburden stratification and conditions, groundwater flow characteristics, etc.).

Methods For Decreasing Infiltration

Ground Surface Sealing:

Ground surface sealing may be accomplished via the use of impermeabilizing agents such as clay (bentonite, "Volclay", etc.) flexible fabric liners, and overlays (bitumen, concrete, etc.).

The impermeabilizing agent may be mixed with the in-situ surface soil and compacted to form a relatively thin "watertight" horizontal barrier. The degree of "watertightness" desired can be obtained by varying the amount of impermeabilizing agent to be mixed with the soil, and by varying the thickness of the zone to be treated.

Liner fabric is often installed by excavating the in-situ soil to a relatively shallow depth (e.g. 1-foot) and then stockpiling

it nearby, placing the liner on the exposed soil surface, and covering the liner with the stockpiled soil material.

Ground surface sealing may also be accomplished by grading, compacting, and surfacing the in-situ soil with a bitumen or other suitable material to form an impermeable membrane.

Optimization of Surface Drainage by Topographic Modification

Infiltration of rainfall or snowmelt can be reduced by increasing the rate of surface runoff. This can be accomplished by grading and contouring the ground surface, and by constructing a network of ditches (terrace and slope ditches) for the expeditious collection and distribution of surface runoff.

Grading and contouring primarily increases the rate of surface runoff by decreasing depression storage (ie., ponding). Terrace and slope ditches expedite the flow of surface water downslope to the main ditch, where it is collected and directed downstream of the area. Ditches should be lined with a suitable material that will inhibit infiltration.

Methods for Decreasing Groundwater Flow

The amount of groundwater flow can be reduced or inhibited by controlling the amount of (1) infiltration from precipitation, and (2) lateral seepage from areas "within" and outside of Basin A'. (Currently, the true bedrock catchment area is not clearly defined, however, groundwater seepage is thought to derive from an area larger than Basin A' and from the lakes area south of the basin). Methods for controlling infiltration have been discussed in the preceding section of this report.

Methods that are feasible for controlling lateral groundwater seepage in Basin A' include (1) regulation of the level of Upper Derby Lake, (Kolmer[10] has stated that Upper Derby Lake is a source of groundwater recharge to Basin A'. By regulating the level of the lake, Kolmer suggests that the amount of groundwater seepage to Basin A' can be controlled), (2) construction of cutoff walls in the overburden, and (3) relocation of contaminated soils from source areas to prepared storage within the basin.

Methods for constructing cutoff walls in overburden are discussed in Appendix D. Portions of Appendix D are excerpted from a report entitled, "Containment/Engineered Storage of Basin F Contents, Rocky Mountain Arsenal."[3]

Concept

The objective of this study (ie: Appendix A, Scope of Work) is to evaluate the "most feasible methods that could be employed for containment of Basin A". The Statement of Work more specifically indicates that the objective of the study is the evaluation of "alternatives to contain polluted groundwater in the vicinity of Basin A at Rocky Mountain Arsenal, Denver, Colorado." (By "in the vicinity of Basin A" is meant Basin A').

Direct containment of polluted groundwater in Basin A' may be accomplished by contructing an impermeable cutoff wall in the overburden to bedrock, thereby enclosing source areas of pollution within the basin. (The lateral extent of contamination of pollution source areas in Basin A', is tentatively assumed to be that shown on available drawings. The "actual" lateral extent will need to be determined by conducting additional investigations). Cutoff walls can be constructed

using the sheetpile, slurry-trench, thin-wall grout screen, or grout-curtain method. Appendix D is a brief discussion on cutoff wall construction methods excerpted from reference number 3.

Indirect containment of polluted groundwater may be accomplished by excavating and relocating contaminated soil from source areas of pollution to engineered storage in Basin A', or by impounding polluted groundwater in Basin A' with an umpermeable cutoff wall located in the bedrock drainage system. (Indirect containment would,for some of the proposed alternatives, allow groundwater to continue flowing out of Basin A'. Future studies may show that the concentration of chemical pollutants after implementation of a particular alternative for containment is "low" or "tolerable").

Future studies may show that the degree and extent of chemical contamination, and the groundwater flow and ground surface infiltration rate in Basin A',is "low". Such a situation suggests that direct/indirect containment is not needed and that the curtailment of any further contaminant migration in the future can be accomplished by some or no surface treatment. If it can be established that the major source of groundwater recharge in Basin A' is derived from the Derby lakes, consideration should be given to draining the lakes and discontinuing their use. The effect that discontinuation of the lakes' use may have on animal life (ie., loss of habitat, etc.) would,however, need to be evaluated.

Implementation of a direct/indirect containment scheme will result in full or partial disruption of the groundwater flow regime upstream of Basin A'. The consideration of the effect that containment will have on the groundwater flow regime is not within the scope of this study.

The groundwater conditions (ie., "true" water table, perched water table, groundwater flow rate, etc.) in Basin A' need to be defined. The groundwater condition will have an effect on the analysis/design/ selection of alternative approaches for containing polluted groundwater in the basin.

General Considerations

The bedrock channel-catchment area model proposed for Basin A' may include other "channels" or drainage features that lead in or out of the basin. With minor exceptions, the available geotechnical information however, does not support the existence of channels other than a_i or a_o. (A few test borings made north of Basin A in Section 36[10] in the purported bedrock-high area, indicated the existence of a relatively thin saturated zone in the overburden.)

The direct/indirect containment of polluted groundwater may consequently result in the impoundment and excessive accretion of groundwater due to recharge by precipitation and/or seepage from areas "upstream" of Basin A'. Extreme situations that may arise as the result of excessive groundwater accretion include (1) "backup" or reverse groundwater flow to areas not currently polluted and (2) rise of the watertable to the groundsurface. (If groundwater flow is reversed along channel a_i as the result of impoundment, so that the groundwater gradient slopes from northeast to southwest, it is possible to introduce contaminants along the southern boundary of the Konikow bedrock-high area south of the Plants area. The southern boundary of the bedrock-high area appears to be a bedrock erosional feature that slopes downward in a westerly direction toward and out of the western boundary of RMA. Reversed flow can be controlled by installing a system

of wells south of the cutoff in channel a_i). A provision must therefore be made for the control, treatment, and disposal of polluted groundwater that is removed by pumping. A consideration of the latter provision is not within the scope of this study. (Other than by pumping, a dewatering method that may prove to be economical and compatible with the basin's soils and chemical pollutants, consists of "wicks" installed vertically in the saturated overburden. The wicks were devised by Japaneese engineers for dewatering compressible soils undergoing consolidation by means of surcharge loading. Water is removed by capillary action and evaporation at the ground surface.)

Excavations to bedrock of the depths proposed in this study (ie., 13 to 40 feet), require for safety reasons that the walls of the excavation be sloped-back or braced. It is usually more economical to perform an excavation by sloping the walls; bracing,on the other hand,often is considerably more time-consuming and expensive.

Excavations below the water table may require that special dewatering methods be used. Because of the handling problems associated with the excavation of contaminated soils below the water table, construction costs can be increased by a factor of 2.

Temporary stockpiling of excavated contaminated soil on the ground surface will present special problems in that leachates draining from the stockpiles will tend to pollute areas that are not currently affected. The ground surface at areas that are set aside for stockpiling should be treated with a temporary seal and diked to impound leachates.

A peripheral cutoff wall can be constructed in the overburden along the entire boundary of Basin A'. The construction of the section of cutoff traversing the Plants area in Section 1 may be unrealistic, however, considering that significant chemical pollution sources may continue to be located outside of the "contained" area. The physical impracticality that construction of a cutoff wall would present in that particular area of RMA, also needs to be considered.

All containment/relocation subapproaches will require a thorough investigation of the "bedrock" surface beneath Basin A'. Information is required on the condition (e.g., degree of weathering, etc.) and properties (permeability, etc.) of the "bedrock." Contaminated groundwater movements directly through the "bedrock" must also be inhibited. This is a necessary consideration in the evaluation of feasibility for each subapproach. Any bedrock-surface feature that could lead to "leaking" of contaminated groundwater has to be sealed by some means (e.g., grouting).[3]

Concurrent with the implementation of a particular alternative approach for containing polluted groundwater will be the discontinuation of all chemical waste disposal in Basin A'. In addition, a policy will need to be established between the leasees of the Plants and other chemical manufacturing areas in the arsenal and RMA, which will eliminate the occurrence of "leaks", "spills", and unauthorized disposal of chemical wastes in or out of the Plants area. Implementation of such a policy would also include provisions for correcting current or potential sources of leaks and spills, improving runoff and storm water collection, treatment, and disposal, and for periodic inspection of the Plants area.

Overland runoff exiting from Basin A' via surface drainage ditches, is expected to transport entrained contaminants eroded from the ground-surface at pollution source areas located in the basin. Once beyond Basin A', the runoff in the drainage ditches has three possible destinations depending on the intensity and duration of rainfall and antecedent basin conditions, and that is, (1) continued transport in the channel, (2) infiltration into the ground, and/or (3) evaporation. Continued transport in the drainage ditch may eventually carry the polluted surface runoff outside of the boundary of RMA. Infiltration of polluted surface runoff may eventually lead to the contamination of the groundwater.

To prevent erosion and transport of chemical pollutants by overland runoff, the ground surface at the source areas will be contoured, graded, and treated. (The degree or type of surface sealing that is implemented depends on the area or areas to be treated in Basin A'). A similar surface treatment may be required along the contaminated sewer and utility lines in Basin A', especially where leaking is or has been prevalent. The collection, treatment, and disposal of polluted runoff originating in Basin A' is not considered within the scope of this study.

Catastrophic Failure

Non-hardening slurry-trench backfill is expected to be more "compressible" than the in-situ soil adjacent to the trench. Lateral movement (ie., "creep") of the soil adjacent to the slurry-trench is therefore likely, especially if structures such as buildings and pavements are located near the trench. The stability in bearing or sliding of the overburden and structures near the trench, needs to be evaluated.

Dewatering to control groundwater table accretion, may induce settlement of the ground surface that may not be tolerable. (Generally, this phenomena occurs when compressible soils are subjected to an increase in confining pressure due to changes in the unit weight of overlying soils, that is, change from a submerged to a saturated unit weight-condition. Based on a review of the available geotechnical information, compressible-type soils do not appear to exist in Basin A'). The volume of some soil materials decreases when pore water is extracted. from them by pumping, which also induces settlement of the ground surface. Settlements such as these can lead to damage of existing structures and pavements. The effect of dewatering on the overburden in Basin A' (and vicinity) needs to be investigated.

Catastrophic failure due to seismic activity (e.g., earthquake, bombing, etc.) needs to be defined in conformity with the particular containment/relocation subapproach selected. More specifically, the subapproach needs to be evaluated with regard to structural stability and construction materials resistance for some rationally selected maximum level of seismic activity. Factors like design earthquake and dynamic properties of in-situ borrow soil materials need to be determined.[3]

Monitoring of the groundwater system, prior to and during construction and operation, is necessary to assess the effectiveness of the particular subapproach implemented for containment/relocation of Basin A'. The monitoring technology required for assessing the effectiveness of the subapproaches considered in this study is available. Monitoring devices include observation wells, piezometers, and underdrain observation locations for water level and water quality studies; inclinometers and settlement plates for measuring earth movements are

also available. Any one or a combination of these devices may be implemented for field monitoring of a particular subapproach.

It is important that a monitoring program be developed and installed as soon as possible to establish general water quality and level prior to construction and operation of the particular subapproach selected. This, with existing data, will establish conditions prior to intervention by the system.[9]

Provisions should be made in order to remedy either a minor or a major (catastrophic) failure of the system implemented for containment/ relocation of Basin A'. The particular remedial treatment required is dependent on the subapproach implemented. Remedial treatment may include sheet-pile, slurry-trench, and/or grouting.

Special on-site medical and emergency facilities are suggested for the immediate treatment of personnel during the course of exploration and construction operations.

Alternatives for Containing Polluted Groundwater

The following is a listing of possible alternative approaches (subapproaches) that can be employed to contain polluted groundwater in Basin A' (The impracticality of implementing some of the subapproaches that are proposed in this report may seem obvious or redundant (ie., when compared to other possible subapproaches); they are nevertheless included in the discussion to illustrate the range of possibilities that may be feasible for containing groundwater pollutants in Basin A'):

Approach I. Direct Containment

1. Peripheral cutoff containing Basin A' north of 7th Avenue (see Figure 8).

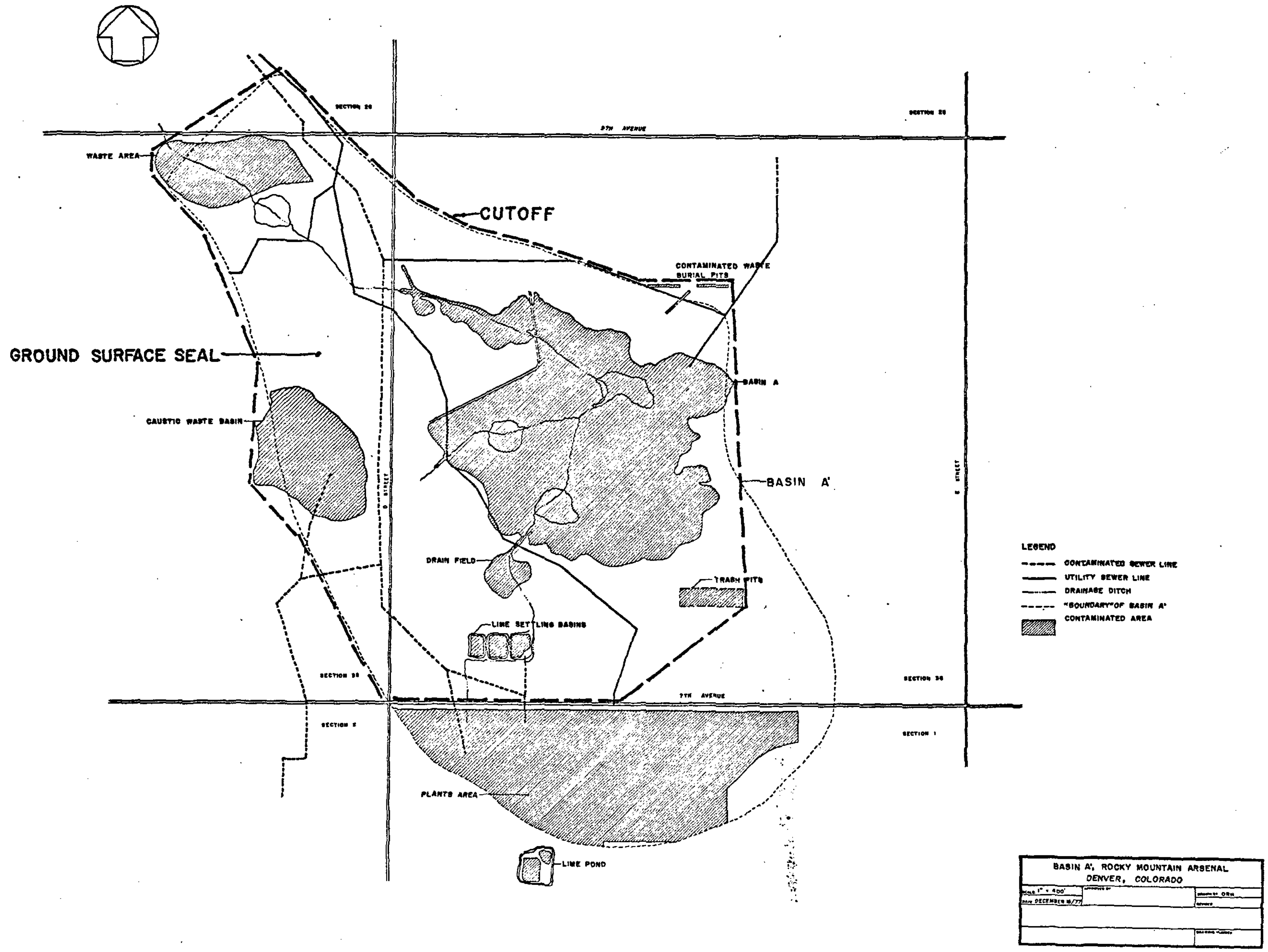


FIGURE 8 : DIRECT CONTAINMENT - SUBAPPROACH II. PERIPHERAL CUTOFF CONTAINING BASIN A' NORTH OF 7th AVENUE

Approach II. Indirect Containment

a. Peripheral cutoff

1. Peripheral cutoff for containing "major" pollution source areas (including relocation of contaminated soil from remaining source areas, to Basin A). See Figure 9.

b. Cutoff impoundment

1. At channels a_i and a_o (see Figure 10).
2. At channel a_o (see Figure 11).
3. Mid-Basin A' (see Figure 12).

c. Relocation of contaminated soil to engineered storage

1. Above grade (see Figure 13 and 14)
2. Below grade (see Figure 15)

Approach III. No Containment

1. Without surface treatment
2. With surface treatment

<u>Method of Implementation</u>

Subapproach I1. Peripheral cutoff containing Basin A' north of 7th Avenue:

The pollution sources that are located in Basin A' can be contained directly by constructing a peripheral cutoff wall in the overburden to bedrock as shown on Figure 8 and Figures D_1 to D_4, Appendix D. For this scheme,it is assumed that a majority of the groundwater pollution sources are located north of 7th Avenue, and that polluted groundwater originating from the Plants area is impounded by the cutoff wall along 7th Avenue. Future geotechnical and groundwater pollution studies, however, may require that Basin A' be contained along its' entire periphery.

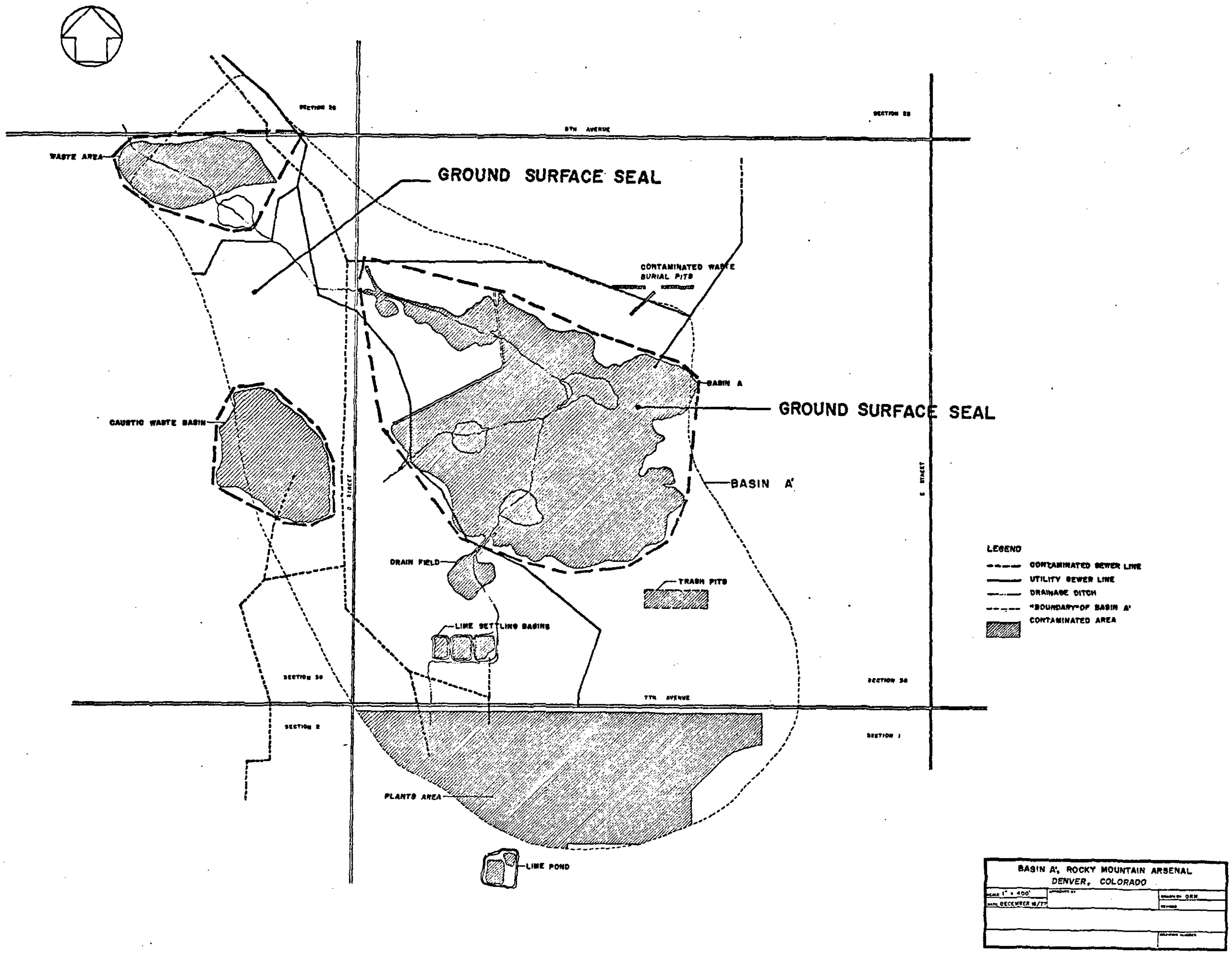


FIGURE 9 : INDIRECT CONTAINMENT – SUBAPPROACH II a1. PERIPHERAL CUTOFF FOR CONTAINING MAJOR POLLUTION SOURCE AREAS

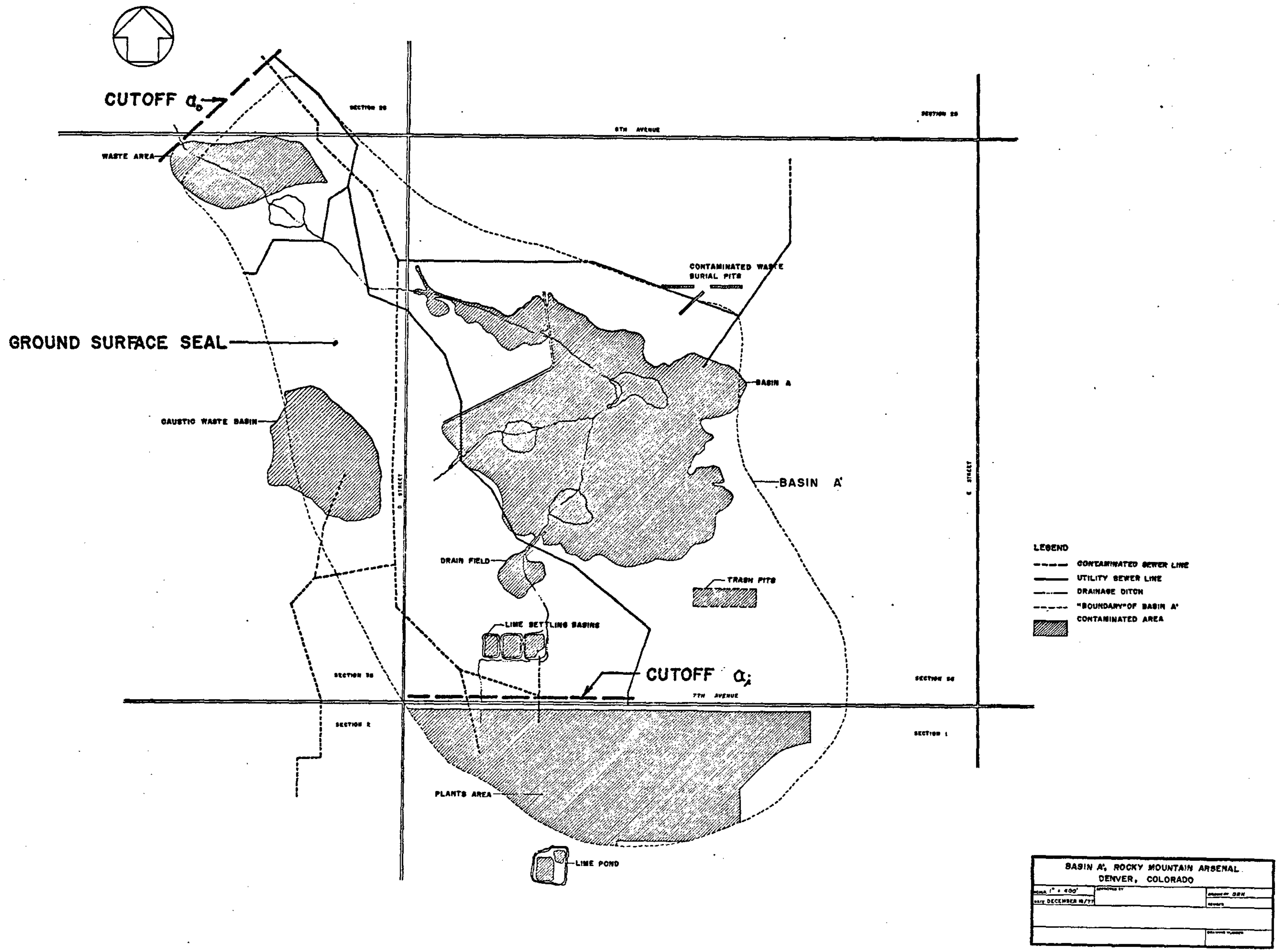


FIGURE 10: INDIRECT CONTAINMENT - SUBAPPROACH IIb1. CUTOFF IMPOUNDMENT AT CHANNELS a_i AND a_o

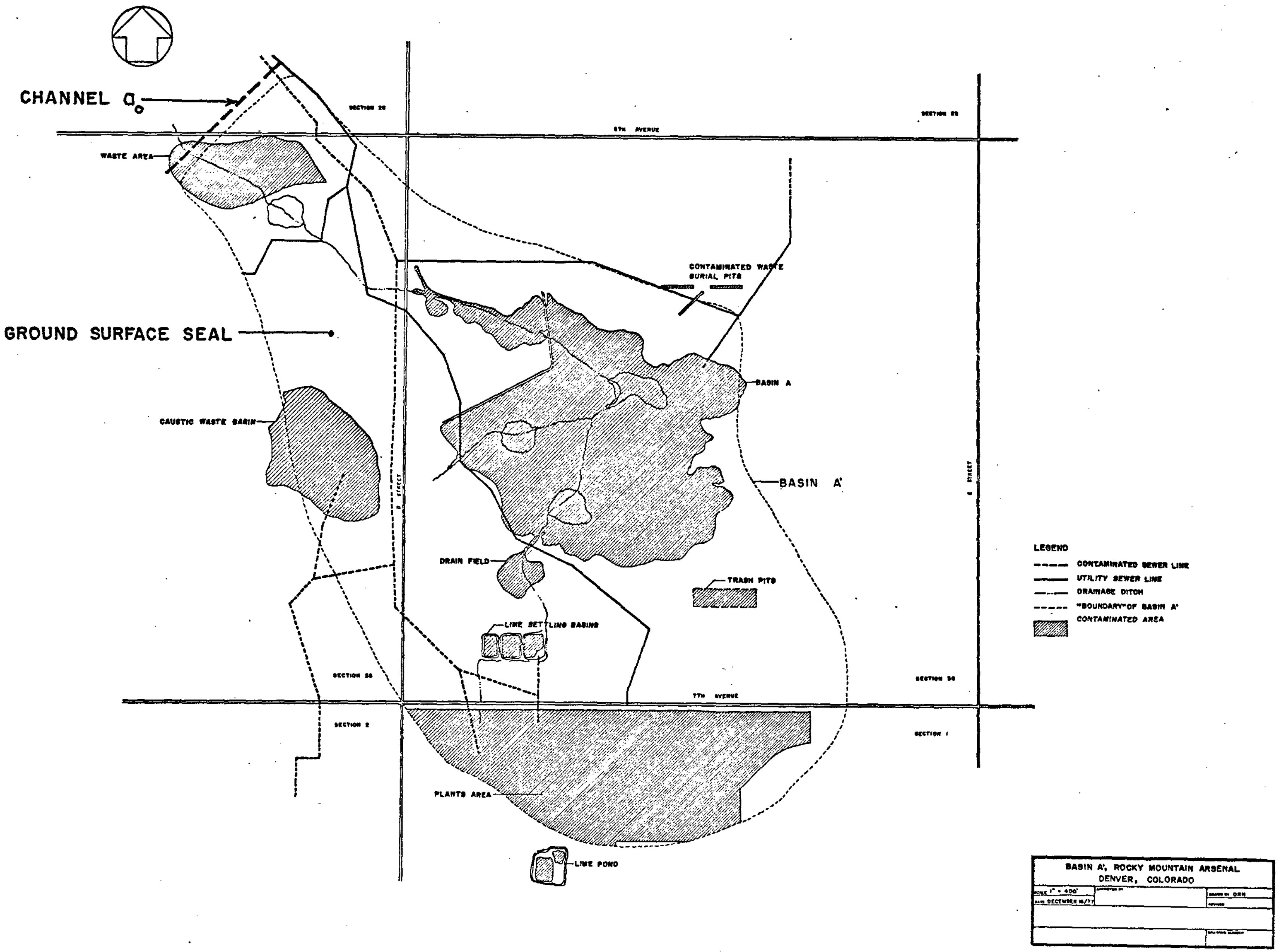


FIGURE II : INDIRECT CONTAINMENT - SUBAPPROACH IIb2. CUTOFF IMPOUNDMENT AT CHANNEL a_0

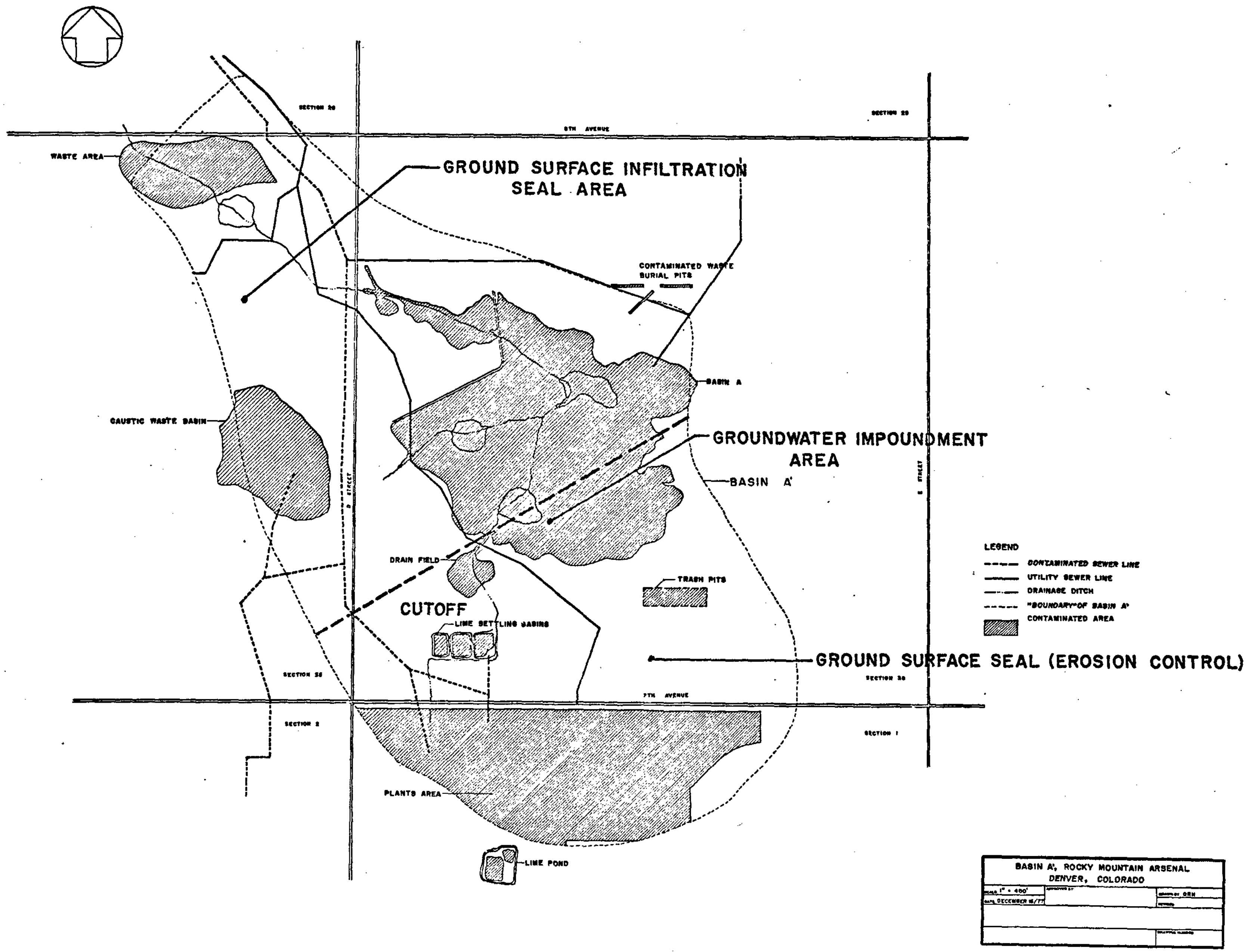


FIGURE 12: INDIRECT CONTAINMENT - SUBAPPROACH IIb3 CUTOFF IMPOUNDMENT AT MID-BASIN A'

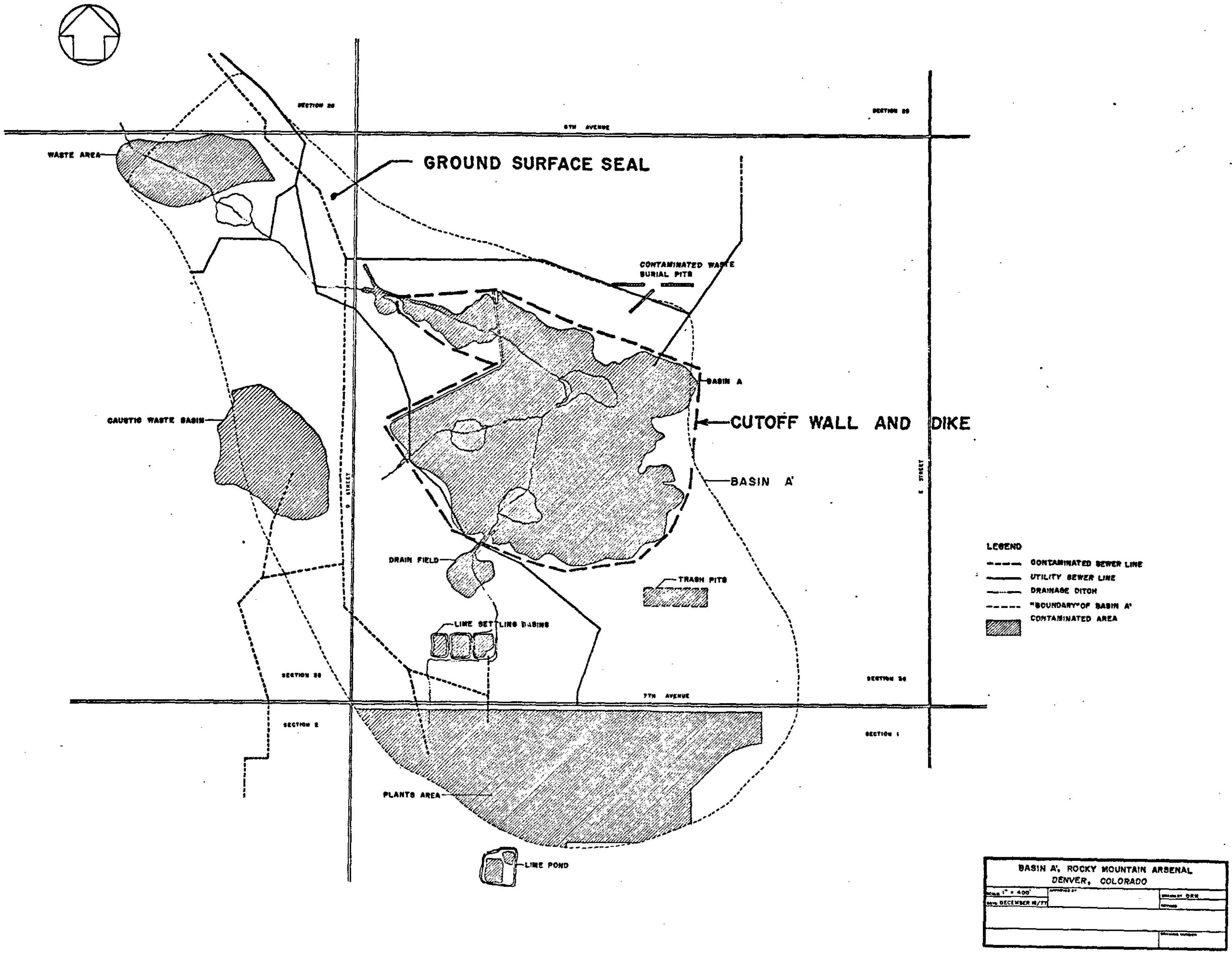


FIGURE 13: INDIRECT CONTAINMENT – SUBAPPROACH IIc1. RELOCATION OF CONTAMINATED SOIL TO ENGINEERED STORAGE ABOVE GRADE

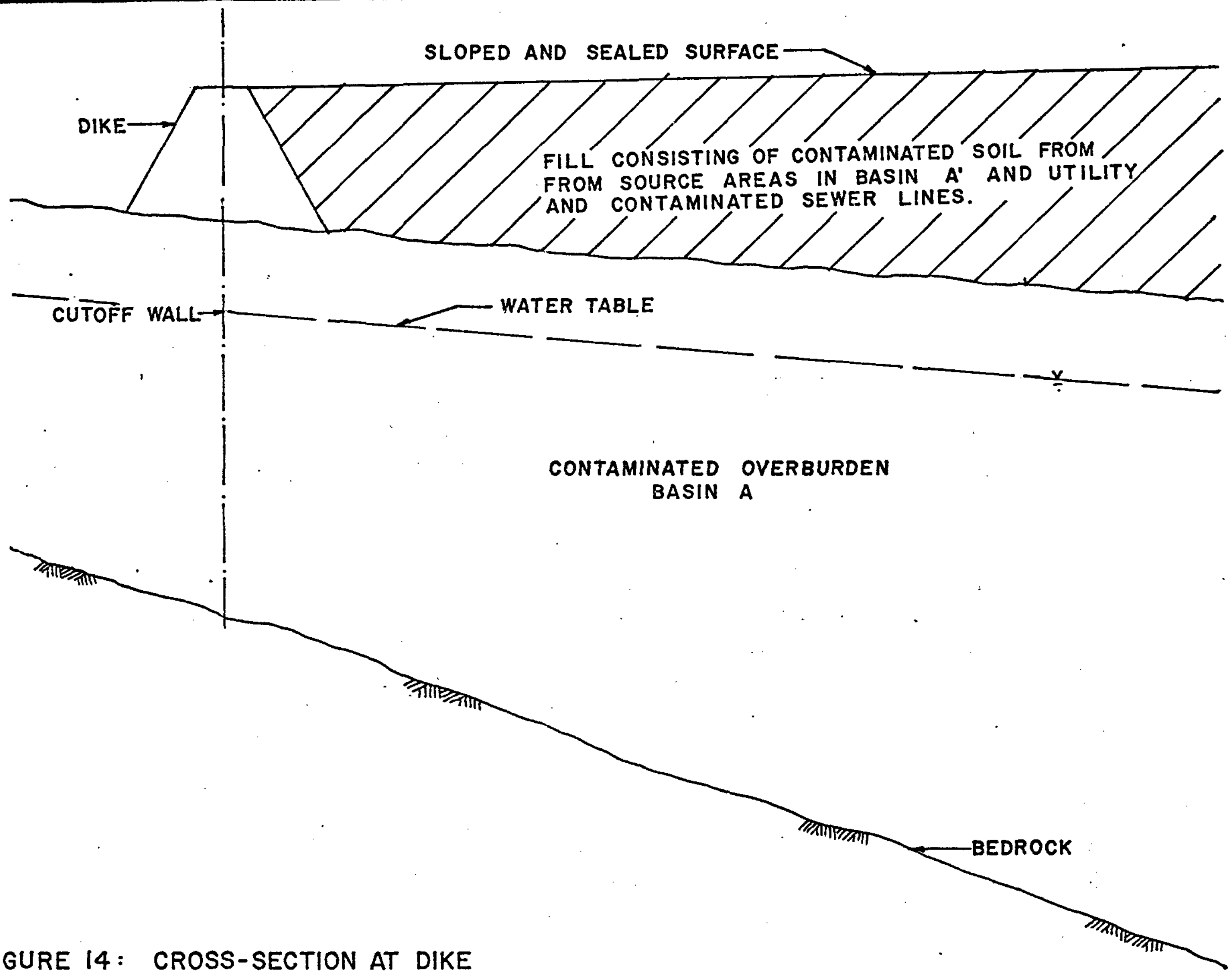


FIGURE 14: CROSS-SECTION AT DIKE

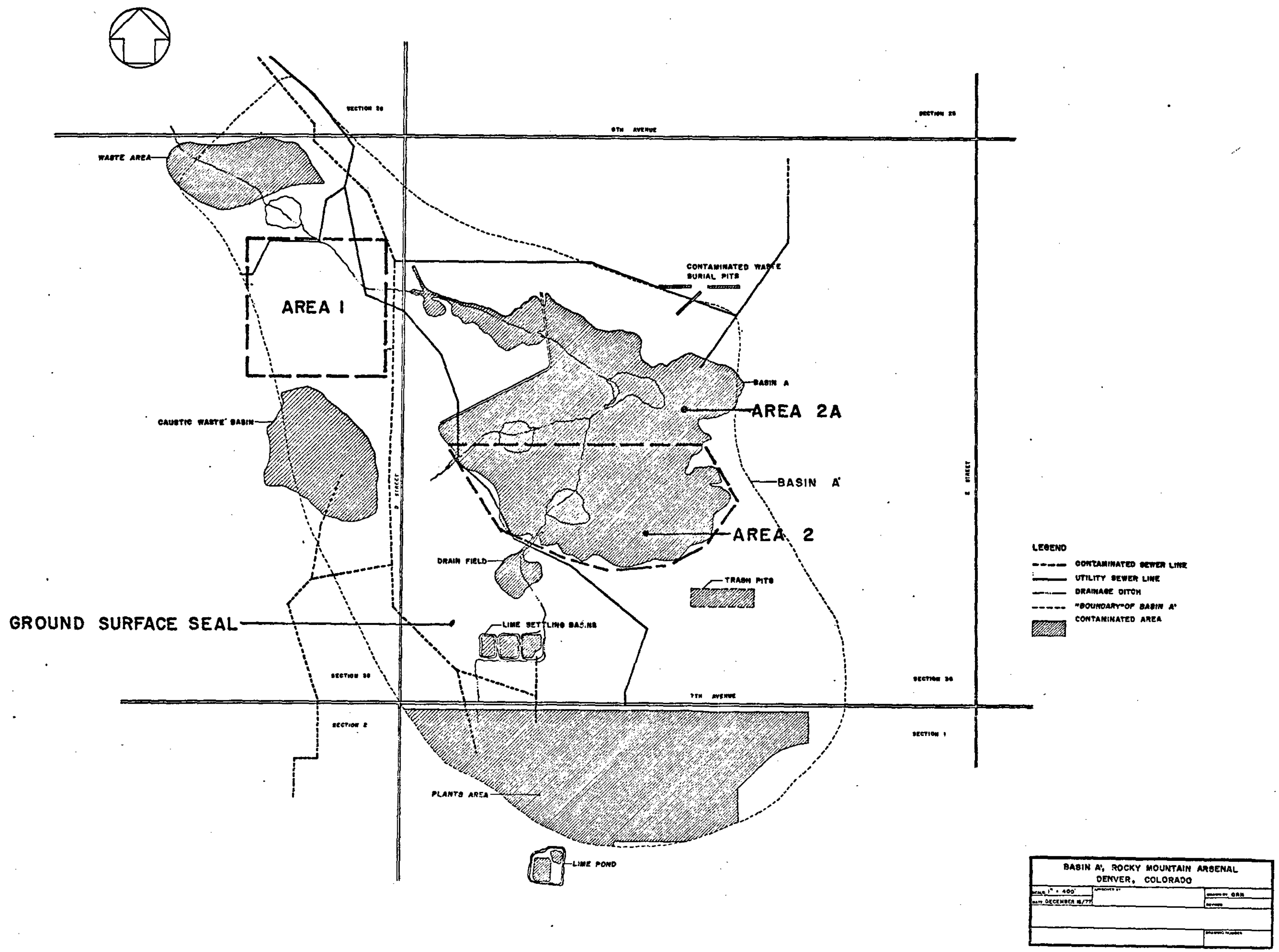


FIGURE 15: INDIRECT CONTAINMENT - SUBAPPROACH IIc2. RELOCATION OF CONTAMINATED SOIL TO ENGINEERED STORAGE BELOW GRADE

Since for this particular subapproach the contaminated sewer and utility lines need not be removed, it is required that they be sealed and capped at the cutoff line.

Ground surface sealing may be required to inhibit erosion.

Subapproach IIa1: Peripheral cutoff for containing "major" pollution source areas:

A cutoff wall can be constructed around some of the "major" pollution source areas as shown on Figure 9. (The length of cutoff wall required for Subapproach IIa1 is not very different from that required for Subapproach Ia1. In addition, containing Reservoir B with a peripheral cutoff wall would produce the same effect as that accomplished by Subapproach IIb2 - Subapproach IIb2 is discussed in a section that follows. It could thus be argued that Subapproach IIa1 should be eliminated from consideration because all of the remaining containment features under IIa1 are redundant). The remaining pollution source areas that are not contained, can be excavated, treated, and backfilled with "clean" in-situ borrow; the contaminated soil obtained therefrom (along with the contaminated sewer and utility lines removed), can be transported to and compacted in the low-lying areas of Basin A. Ground surface sealing is required.

The cutoff at Reservoir B would be expected to act as an impoundment to groundwater in channel a_o. Pumping to reduce groundwater accretion in this area may be required.

Ground surface sealing, to reduce or eliminate erosion and overland transport of contaminants from the Basin A' area north of 7th Avenue, is required.

Subapproach IIb1. Impoundment of polluted groundwater at channels a_i and a_o:

The polluted groundwater that migrates northwest from Basin A', can be stopped by constructing cutoff walls in the overburden across channels a_i and a_o, as shown on Figure 10. The cutoff in channel a_i would prevent polluted groundwater (recharge, etc.) originating south of 7th Avenue from entering Basin A' north of that point. The cutoff in channel a_o would prevent groundwater from exiting Basin A'.

To reduce groundwater recharge by infiltration in Basin A', varying degrees of treatment will be required to seal the ground surface in different areas of the basin. (For this subapproach, groundwater infiltration may be of a magnitude that is tolerable; that is, control of the groundwater level may not be necessary. If this is true, it may also be beneficial to permit or perhaps enhance infiltration, thereby maintaining or reducing overland runoff).

Future geotechnical studies may show, however, that a cutoff wall at channel a_o will suffice to contain all polluted groundwater that originates in Basin A' without the need for a cutoff at channel a_i.

Subapproach IIb2. Cutoff impoundment of polluted groundwater at channel a_o:

Polluted groundwater migrating from Basin A' can be stopped by constructing a cutoff wall in channel a_o as shown on Figure 11. A system of wells may be required on the upstream side of the cutoff for controlling the groundwater level.

Groundwater surface sealing for reducing erosion and infiltration may be required.

Subapproach IIb3: Cutoff impoundment of polluted groundwater at mid-Basin A':

The major groundwater pollution sources in Basin A' are suspected or reported to be located in the southwest corner of Section 36, including the Plants area. The pollution sources in that particular area may be contained by constructing a cutoff wall as shown on Figure 12.

The ground surface north of the cutoff wall is sealed mainly to inhibit infiltration in that part of Basin A', whereas the ground surface south of the cutoff is sealed to inhibit erosion and transport of chemical pollutants north of the proposed barrier.

Subapproach IIc1. Relocation of contaminated soil to engineered storage above grade:

Contaminated soils from all pollution source areas in Basin A' can be excavated and stored in a diked area constructed to encompass Basin A, as shown on Figure 13. (Contaminated sewer and utility lines would be dismantled and buried in the diked area). The dike can be constructed of a suitable borrow soil over a sub-surface cutoff wall as shown on Figure 13 and 14. (An alternate way of constructing the dike other than with soil, is to extend the sheetpile above the ground surface to form a "wall" around Basin A. The interlock of the sheetpile sections would have to be made as "watertight" as possible to prevent leakage of contaminated leachates to the surrounding areas in Basin A'). The excavated areas could be backfilled with "clean" in-situ borrow soil.

The surface of the contaminated soil that is stored within the confines of the dikes area would be sealed to prevent erosion or infiltration by runoff. A similar treatment may be required over the rest of the basin area.

Excavation would include the removal and transport of moist and of saturated contaminated soil. Handling of the saturated soil could present special problems associated with excavation, transport, and placement in the diked area. Methods for accomplishing these tasks need to be evaluated.

This particular subapproach would allow groundwater to continue flowing through Basin A'. If chemical contamination originating from the Plants area is "eliminated" or considerably reduced via the formal establishment of policy, etc., and some degree of ground surface sealing to inhibit infiltration is carried out in Basin A', the groundwater is expected to contain little, if not a minimal (tolerable?) concentration of chemical pollutants.

Subapproach IIc2. Relocation of contaminated soil to engineered storage below grade:

Contaminated soils in the pollution source areas of Basin A', can be relocated to engineered storage below grade in Areas 1, 2, and 2a, as shown on Figure 15. Area 1 is a sealed pit prepared for the purpose of storing contaminated soil excavated from the Waste Area (Reservoir B) and Caustic Waste Basin. (The stockpiled soil excavated from Area 1 is intended for use as backfill for the Waste Area and Caustic Waste Basin). Contaminated soil and debris from the Contaminated Waste Bural Pit, Trash Pit, Lime Settling Basins, and Drain Field, and the contaminated sewer and utility lines will be moved to Areas 2 and 2a.

Construction operations to relocate contaminated soils and other materials to Areas 2 and 2a will be conducted in stages as follows:

1. Excavate the contaminated soil in Area 2 and stockpile on a temporarily sealed surface in Area 2a;
2. seal the excavation walls and floor in Area 2;
3. excavate and relocate contaminated soils and other materials from Lime Settling Basin, etc., to Area 2 (This stage also includes returning contaminated soils stockpiled on Area 2a to Area 2. It should be noted that the ground surface elevation in Area 2 after all backfilling operations are completed, will be higher than before backfilling; the "excess" amount of soil will be distributed over Area 2 and 2a. This part of the work, that of the distribution of excess soil, is to be carried out at a latter stage of construction.);
4. backfill Lime Settling Basins area, etc., with "clean" in-situ borrow soil;
5. excavate Area 2a and stockpile contaminated soil on a sealed surface in Area 2;
6. seal the excavation walls and floor in Area 2a;
7. return contaminated soil stockpiled in Area 2 to storage in Area 2a (including the distribution of "excess" soil over Area 2 and 2a); and
8. grade and seal the ground surface in Basin A to inhibit infiltration or erosion by precipitation. (Areas other than Basin A in Basin A' will also be sealed for similar reasons).

Subapproach III1 and III2. No Containment:

Without the need for containment of polluted groundwater, some or no surface treatment may be required to reduce soil erosion and overland transport of contaminants by runoff.

If, in fact, the Derby lakes are found to be significant sources of groundwater recharge in Basin A', consideration should be given to draining them. This possibility would make Subapproach III1 and III2 especially attractive alternatives.

Feasibility Evaluation

The forseeable types of studies that are required for a detailed quantitative feasibility evaluation are shown in Appendix I. The studies are divided into eight groups and include geotechnical, seismic, materials compatability, handling hazards, stability, contaminated soil, contaminated groundwater, and environmental studies. Sub-studies within each of the study groups are also shown in Appendix I.

Relative to RMA, most of the proposed studies are commonly performed and/or are self explanatory. Examples of some that are not include soil erosion, groundwater/runoff and infiltration, and groundwater recharge by rainfall and lake seepage.

The compatability between contaminated soil and polluted groundwater, and different types of materials such as liners, impermeabilizing agents (bentonite, etc.), and cutoff construction materials, needs to be evaluated considering short and long-term use. (Because the materials compatability tests may in some cases be highly time-dependent, there is no assurance that one year of testing time will be sufficient for any particular material).

The literature search, field sampling, and laboratory set-up portions of the compatability tests do not vary very much between subapproaches. The total costs, therefore, may be much lower than that shown in Appendix H. (In addition, if the study part of the work on Basin A'

is performed concurrent or subsequent to that for Reservoir F, by the same contractor, additional savings in study costs may be realized.

The estimates for time and costs given for the materials compatability studies are crude, however, since the time and costs will depend highly on (1) number of construction materials and in-situ interaction combinations (compatability) that need to be investigated for each subapproach (2) whether or not some of the compatability studies have been performed or are under way, and (3) the test time that may be required to adequately evaluate compatability.

The rate of groundwater and surface water flow needs to be known before a particular subapproach can be rationally selected for a quantitative feasibility evaluation. The determination of groundwater and surface water flow rates requires that information be obtained concerning the runoff-infiltration regime, soil erosion and transport characteristics, and groundwater recharge condition prevailing in Basin A'.

Estimates of cost and time schedules for all of the subapproaches that are considered in this study are shown in Appendix E. (The cost and time estimates do not include a consideration of groundwater-level control, treatment, or disposal.) The cost estimates shown in Appendix E are based on the estimated construction unit costs shown in Appendix F1[3], and on the approximate dimensions, areas, and volumes (for Basin A' and included pollution source areas) shown in Appendix F2.

Estimates of cost and time schedules for the different subapproaches varied between 0.0 and $17,050,000. ($3,350,000., average), and zero and 27 months (10.9 months, average), respectively.

With the exception of Subapproach III1, the type, degree, and extent of surface treatment required for the implementation of each subapproach varies. The ratio of the cost of surface treatment and cutoff construction varies between 0.8 and 78.2 for the subapproaches considered in this study (13.6 average).

Some of the advantages/disadvantages for constructing any particular subapproach have been discussed in previous sections of this report. These include for example, problems associated with excavating and stockpiling contaminated soils that are excavated from below the groundwater table, and the relocation of saturated contaminated soils and other contaminated debris, etc.

Considerable uncertainty exists in the efficacy of containing Basin A' as proposed in Subapproach I1. (About 3.8 miles of cutoff is required to contain Basin A' to 7th Avenue). The limits given for the boundary of Basin A' are arbitrary because (1) the Konikow bedrock high boundaries have not been conclusively defined, (2) all of the pollution source areas in the vicinity of Basin A' have not been defined adequately, and (3) because relatively little is known about pollution, etc., in the Plants area.

The function of the cutoff for most of the contained area south of channel a_o is also questioned. Since drainage is assumed to occur through channels a_i and a_o, the cutoff wall sections act mainly as barriers to groundwater seepage into Basin A' area, with little if no beneficial effect in containing polluted groundwater. The greatest benefit for containing polluted groundwater appears to be realized at channel a_o.

Containment of Reservoir B as proposed in Subapproach IIa1, is expected to have the same effect as that of Subapproach IIb2, that is

the curtailment of polluted groundwater flow northwest of Basin A'. For this reason, all of the containment/relocation and surface treatment work proposed in Subapproach IIa1 south of Reservoir B may be redundant.

Cutoff impoundment of polluted groundwater does not require that contaminated soils be relocated or that as much length of cutoff wall be used as for Subapproach I1 or IIa1. About the same degree of surface treatment (primarily for erosion control) is required for Subapproach IIb.

Of the three cutoff containment subapproaches, IIb2 is favored because its implementation requires the shortest length of cutoff wall. Consequently, the construction time and costs for Subapproach IIb2 is less than for all subapproaches where cutoff walls are proposed.

Relocation of contaminated soil to engineered storage above or below grade requires, in addition to cutoff wall installation and surface treatment, expensive excavation, stockpiling, and backfill operations.

No containment, with surface treatment (Subapproach III2), would be the most obvious choice if its implementation were found to be feasible. (Surface treatment would be required for soil erosion control). Based on a review of available information concerning groundwater pollution and soil contamination in Basin A', it does not appear that "implementation" of Subapproach III1 is feasible.

The subapproaches that are to be studied in more detail are shown in Appendix G. These include Subapproach IIb2 and III2. Their selections are based on an evaluation of available information (geotechnical, etc.), the bedrock drainage model proposed for Basin A', and estimated construction time and cost.

Subapproach IIb2 is about 2.5 times less expensive to construct and can be constructed about 3 times faster on the average compared to the other methods. For Subapproach III2, the same comparison is about 1.5 and 2, respectively.

The rationale used for deleting subapproaches from further study has to do with construction time, costs, and feasibility, safety, stability, and expected effectiveness. In evaluating feasibility, however, the cost, and particularly the time required to make a detailed quantitative feasibility evaluation, need to be carefully considered in addition to construction time and costs.

Groundwater Regime

A containment/relocation subapproach that encroaches on the saturated zone above bedrock may disrupt the groundwater regime "downstream" of Basin A'. That is, the containment scheme may act as a diversion/cutoff to the flow of groundwater. The diversion may effect a change in the relative amounts of groundwater discharge that flow through and out of RMA.

Consideration of the disruption of the groundwater regime by the implementation of a containment/relocation scheme is not within the scope of this study, but warrants further studies.

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Appendix A

Scope of Work, PMO, CDIR
Aberdeen Proving Ground, Maryland

STATEMENT OF WORK
TCN: 77-363

SCIENTIFIC SERVICES PROGRAM
STAS

1. General

The services are required of an engineer to perform an evaluation of alternatives to contain polluted groundwater in the vicinity of Basin A at Rocky Mountain Arsenal, Denver, Colorado.

a. From the inception of Rocky Mountain Arsenal until 1957, industrial wastes generated by the Arsenal (and commercial companies leasing facilities at the Arsenal) were dumped into an unlined waste basin termed Basin A. After 1957, industrial wastes were disposed into a lined basin (Basin F). The switch from an unlined to a lined basin came about as a result of identified groundwater pollution associated with disposal in the unlined Basin A.

b. Since the initiation of the Army's installation restoration program, Basin A has been suspected as a major source of groundwater pollution. Pollution plumes of diisopropylmethylphosphonate (DIMP) have have been traced back to Basin A. This work, as well as independent studies and reports, label Basin A as a major source of groundwater pollution at RMA.

c. Because of the evidence showing Basin A to be a serious pollution source, a Basin A treatment study program will be initiated in FY78. This program will be primarily aimed at treatment alternatives development. These treatment alternatives will be evaluated along with Basin A containment alternatives. The most cost effective and environmentally sound system will be selected for implementation.

2. Objective

This study will be an engineering evaluation of the most feasible methods that could be employed for containment of Basin A.

3. Specific Tasks

a. A listing of possible alternatives should be made. Each alternative should be described as to its design (concept) and method of implementation. Sufficient information should be presented on each method discussed so that a qualitative evaluation of the method's potential feasibility can be made. Thus, any obviously impractical methods can be eliminated before the more expensive and time-consuming quantitative evaluation is started.

Attachment 2

Incl

b. For each of the presented methods, the required process, handling, and investigative type studies that would have to be completed to obtain a detailed quantitative feasibility evaluation should be enumerated and discussed. These studies would include considerations such as compatability of contaminated groundwater with materials used in the containment concept, soil and groundwater handling studies to identify potential pitfalls and problem areas in the proposed methods, catastrophic failure considerations, the types of monitoring systems that could be installed for early detection of containment leaks, and what immediate remedial measures could be employed or built-in if leaks in a containment or storage system did occur.

c. From the information presented in paragraphs 3a and 3b above, a qualitative feasibility evaluation should be done. The methods that are obviously not feasible should be dropped from consideration. A discussion of reasons for deletion of a method should be presented.

d. For the methods remaining in consideration cost and time schedule estimates should be prepared for:

(1) Determining detailed quantitative feasibility.

(2) Complete accomplishment of each alternative method being considered.

e. From all of the above data, a final qualitative evaluation should be made. From this evaluation, the methods to be studied in more detail should be presented. The constraints under which this study is to be conducted are listed and at Attachment II:

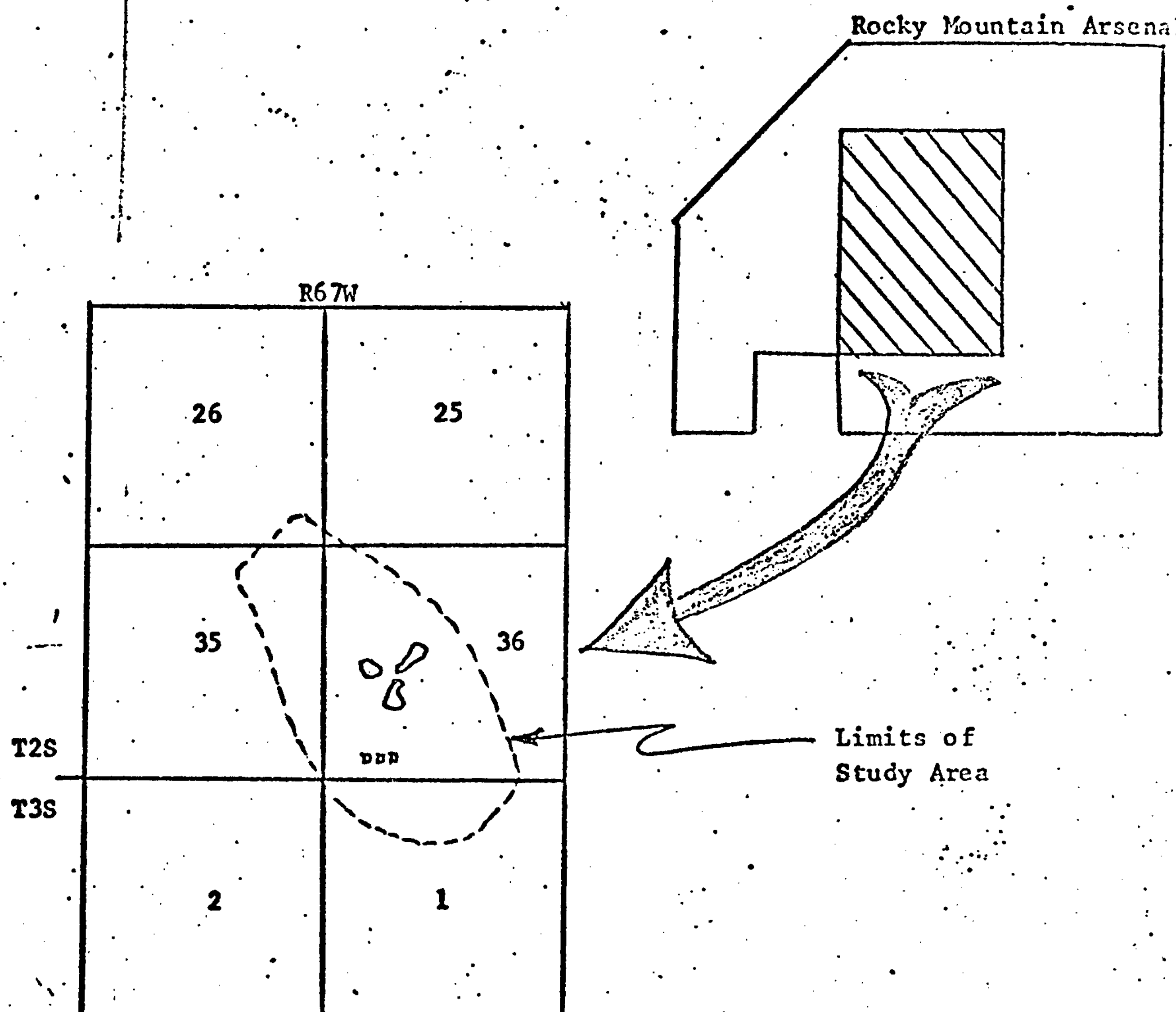
(1) Consider the most feasible methods from a qualitative standpoint only.

(2) The dimensions of Basin A are the peripheral limits as shown in the figure attached and veritically down to impermeable bedrock.

(3) Groundwater movements and/or contamination migration are not to be considered.

(4) No further discharge of waste material will be made into the basin.

ATTACHMENT II



Appendix B

Geologic Sequence

Geologic Sequence

Well No.	Overburden: Eolian Sand	Overburden: Alluvium	Formation
4	Sandy silt; fine silty sand	Verdos:* Clayey silt; clayey sandy silt; clayey silt, contains very coarse gravel; coarse sand contains small cobbles; fine to medium sand, contains very coarse gravel; coarse gravel, sand, and small cobbles; fine sand	Dawson (upper part): fine sand, contains layers of clay and silt; siltstone
5	Silty fine sand; clayey fine sandy silt; silty clay	Louviers: silty fine sand; fine to medium sand; coarse sand; silty clay; sandy coarse gravel	Dawson: shale
16	Sand; clay	Broadway: Sand and gravel	Dawson (upper part) sandstone; shale
34	--	Verdos:	--

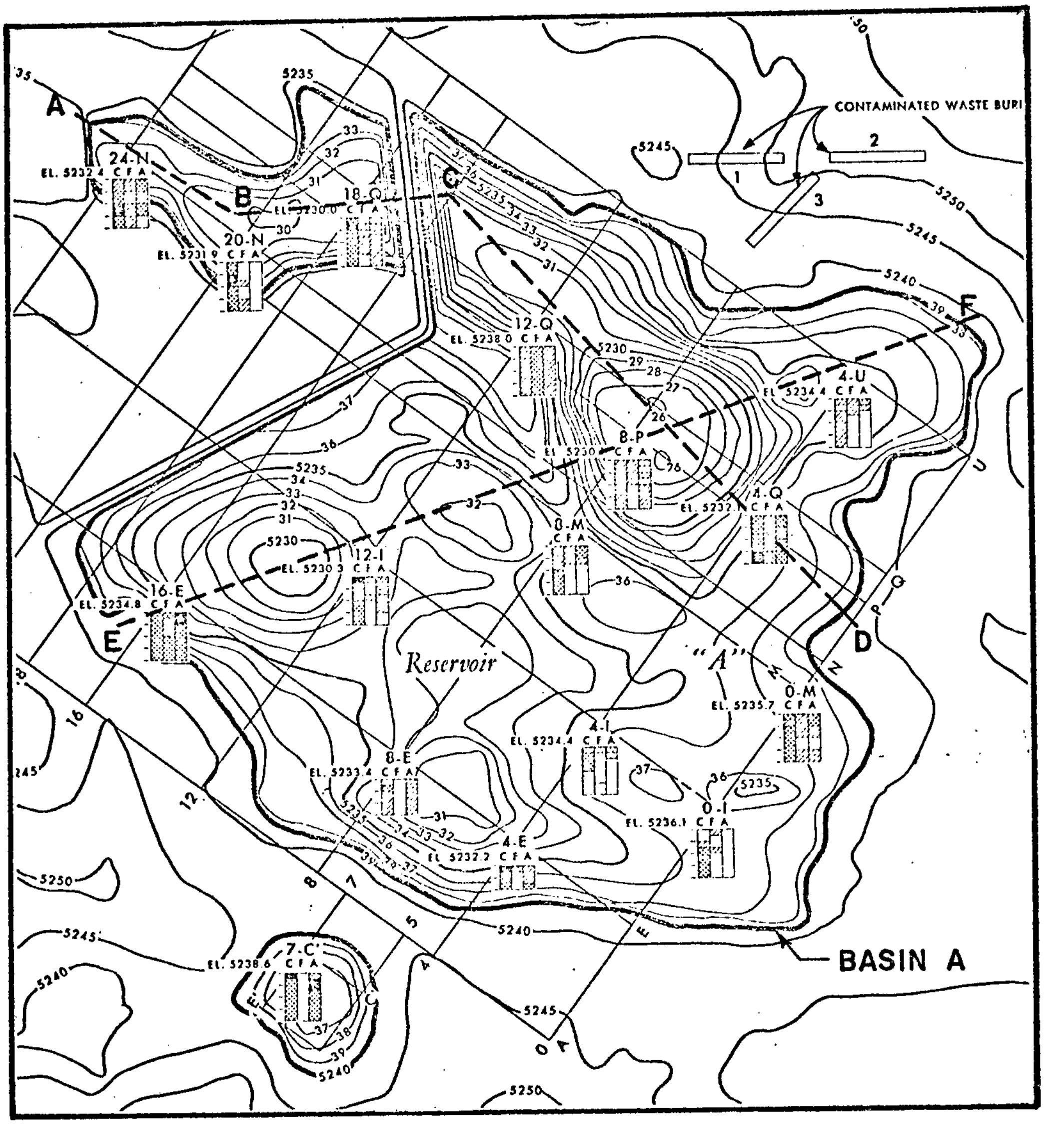
Note: Total depth of W-34 is 12,045 ft.

The stratification given in a report[12] for four wells (W-4, W-5, W-16, and W-34) near Basin F describe the eolian sand and alluvium (soil overburden) and geologic formation at the site

* Order of materials is given according to depth, top to bottom

Appendix C

Location of Bed-Sampling Points in Basin A (for determining soil contamination by Chloride, Fluoride, and Arsenic). Reproduced from Reference Number 7.



LEGEND:

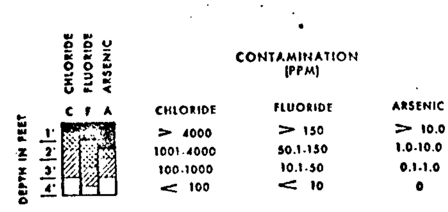


FIGURE CI : LOCATION OF BED-SAMPLING POINTS IN BASIN A (FOR DETERMINING CONTAMINATION BY CHLORIDE, FLUORIDE, AND ARSENIC - REPRODUCED FROM REFERENCE NUMBER 7)

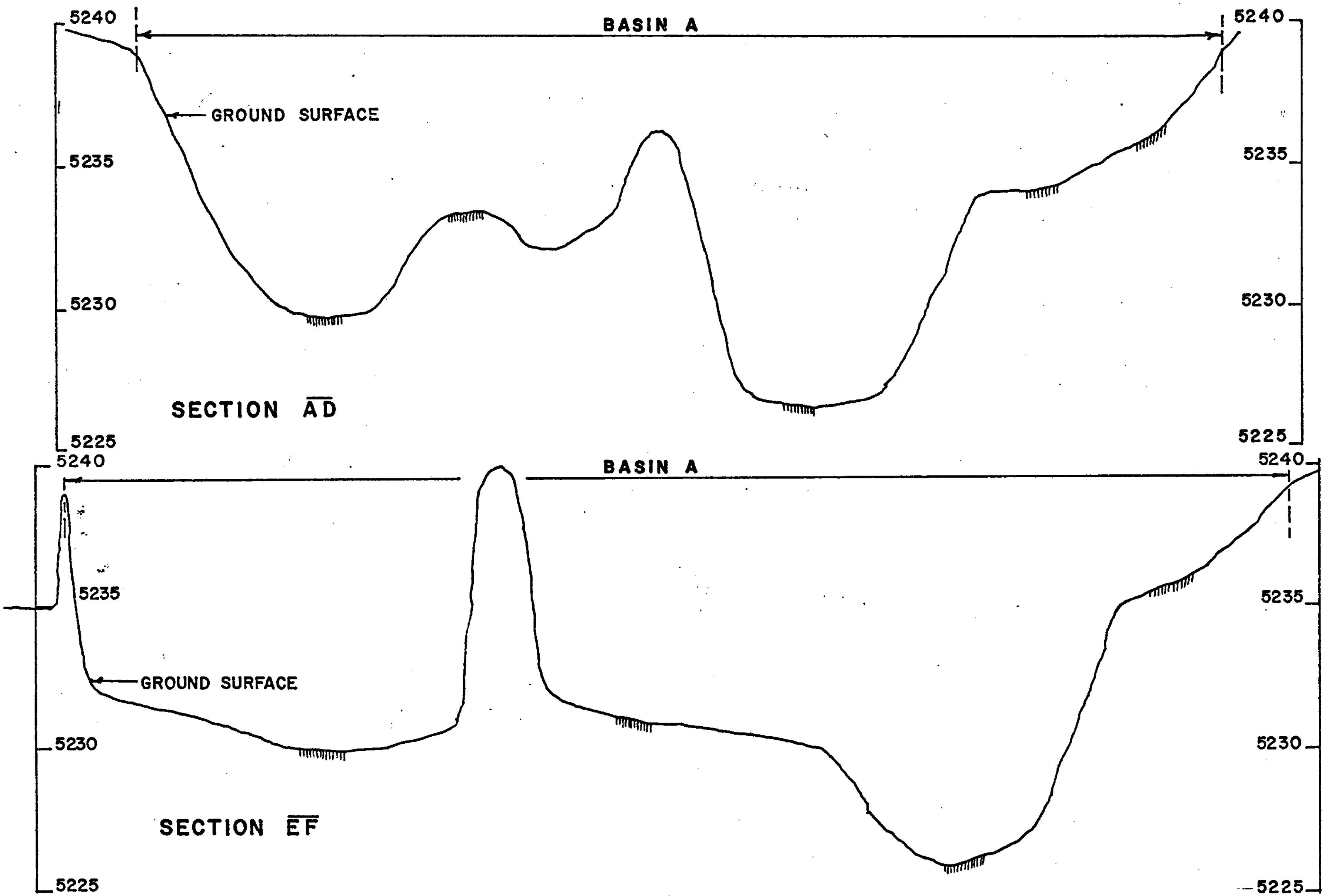


FIGURE C2 : CROSS-SECTIONS AT BASIN "A"

Appendix D

Groundwater Cutoff Methods

Groundwater Cutoff Methods

The following is a discussion on various methods that are feasible for constructing groundwater cutoffs (barrier) in Basin A'. Portions of the discussion are excerpted from a report entitled, "Containment/ Engineered Storage of Basin F Contents, Rocky Moutain Arsenal."[3]

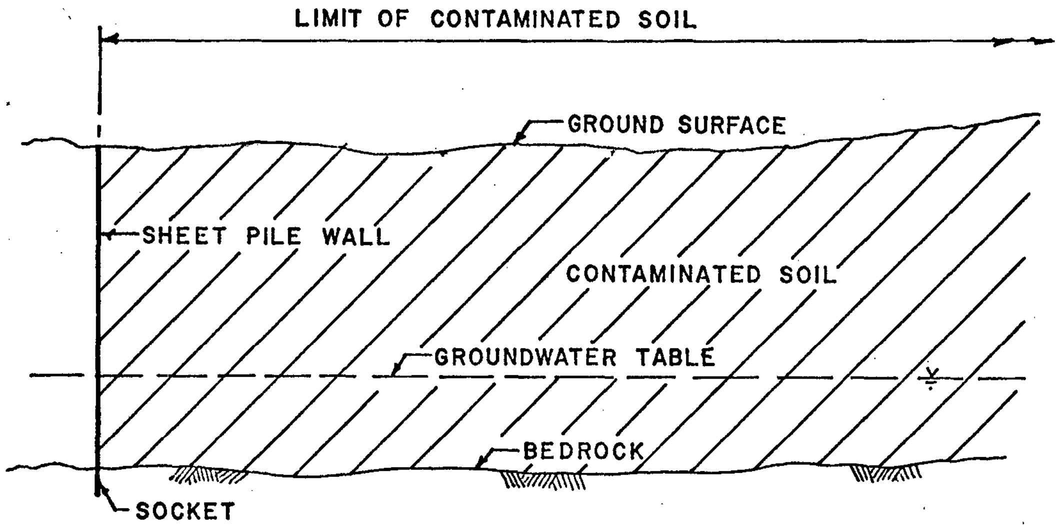
Sheetpile Cutoff

Interlocking sheet-pile sections (e.g., U. S. Steel's "MZ" and "MP" sections) can be driven or vibrated to and socketed into the impervious bedrock to form a "seal." Sheetpiling can be driven or vibrated into place in most soil deposits and conditions, offering structural strength and some degree of "water-tightness" provided by interlocking of individual sheet sections (see Figure D1). The possibility exists that some pressure-grouting will be required where the desired water-tightness of the interlock of bedrock-sheetpile interface is not obtained.

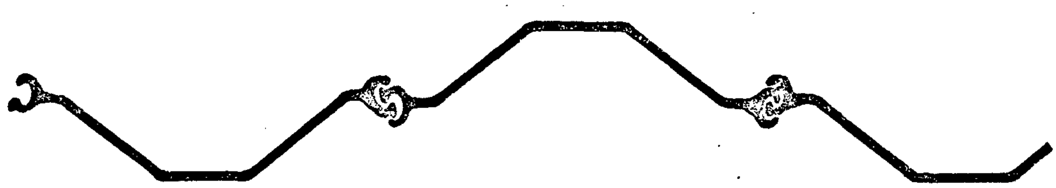
Slurry Trench

A slurry trench is an excavated, continous, narrow vertical slot, the walls of which are supported by a bentonite slurry during the progress of excavation or backfilling (see Figure D2). As soil is excavated from the trench, bentonite slurry is added at a rate such that the trench remains filled at all times.

Slurry trench excavation may be accomplished using backhoes, draglines, clamshells (e.g., Menck mechanical slurry trench clamshell), and other trenching machines (e.g., Tone Longwall drill). Selection of the trenching machine for a particular project is primarily dependent on the desired depth of trench and completion time.



A. CROSS-SECTION AT BOUNDARY OF CONTAMINATED AREA-SCHEMATIC



B. DETAIL OF SHEETPILE SECTION

FIGURE DI : SHEETPILE CUTOFF

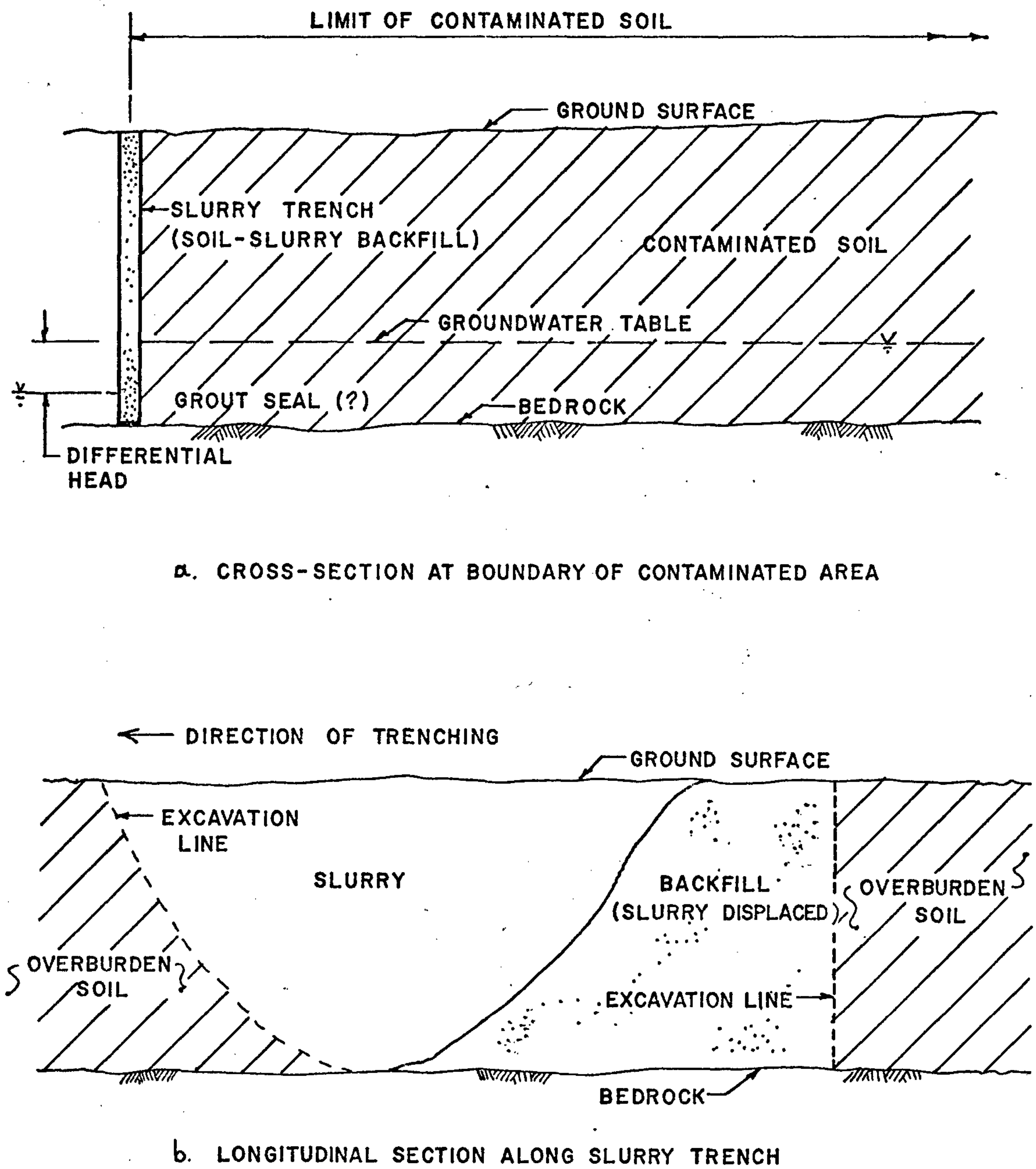


FIGURE D2 : SLURRY - TRENCH CUTOFF WALL

Once the trench has been excavated, it can be backfilled using in situ soil and/or select borrow material blended with bentonite slurry to produce a well graded mix of low permeability. (Walls that are constructed using graded mixtures of soil and bentonite without cements or other hardening agents primarily act as water barriers). Where a "rigid" wall is required, the slurry trench is backfilled with tremied concrete, which may or may not be reinforced. Semirigid walls may also be constructed using a bentonite-cement mix- "self-hardening slurry." Figure D2b illustrates a procedure that is used for constructing barrier type cutoff walls. Since the backfilling operation is commonly intended to progress at the same rate as the trenching operation, the slurry that is displaced by the backfill is used in the extension of the trench (see Figure D2b). Backfill is placed in the trench by using a clamshell or other suitable device. The criteria that are used in designing the barrier material for a slurry cutoff trench is that it be of low permeability and safe from piping. Proper particle-size gradation of the backfill materials will help to minimize post-construction settlement.

Slurry-Trench Bedrock Seal (Socket)

The slurry-trench bottom has to be "keyed" into an impervious material in order that the barrier produced be as watertight as possible. As a precaution during construction, split-spoon samples are often taken about every 50 ft along the slurry trench to make sure that the cutoff wall is properly socketed into the impervious material. In some cases, the bottom of the trench (bedrock contact) is grouted to provide a watertight seal.

Trench Width

A rule of thumb, used by the industry for determining the width of trench required, is 1 ft of width for every 10 ft of differential

head.[18] The width is also a function of the particle-size gradation of the backfill and of the overburden soil. The width of the trench that can be excavated is dependent on the type of trenching equipment that is available (i.e., size of bucket, etc.).

The construction of a slurry trench often requires that a guide-wall be built on the ground surface. The guide wall is used in order to support the trench against surcharge pressures that are produced by heavy construction equipment in the vicinity of the trench. They also aid in protecting the sides of the trench at the ground surface against scouring action produced by digging equipment or during pumping of fresh slurry. They act as a guide to the grab during excavation and as a reservoir for the slurry prior to trench excavation. The guide wall also helps to define the alignment of the trench during construction.

Rate of Slurry Trench Construction

The rate of slurry-trench construction is dependent on the type of cutoff wall desired. The rate for panel excavation with reinforced tremie wall is reported to vary from 16 to 27 ft^2/hour (the tremie placement rate varies from about 1060 to 1235 ft^3/hour).[19] The rate for panel excavation using a self-hardening bentonite-cement mix with cement retarder varies from 54 to 97 ft^2/hour.

Materials Compatibility Studies (see Appendix I)

Future compatibility studies may show that it is necessary to mix the slurry and the backfill materials with off-site water that is not contaminated. Some reasons are that the (a) groundwater may not be in sufficient quantity in the trench in order to satisfy the water requirements for the project, (b) slurry that remains after construction of the cutoff wall will have to be disposed of, and

(c) bentonite (properties of) in the backfill mix may be affected by the chemical contaminants in the groundwater.

A similar conclusion may be reached concerning the suitability of using in situ and/or borrow materials for the backfill. It may be, for example, necessary to either (a) "wash" the excavated soil using some process or (b) use borrow materials. If borrow materials are used, then consideration for the disposal of excavated soil is required.

The effects, therefore, that the contaminated groundwater will have as a "mix" water with slurry or with backfill, or in situ as groundwater adjacent to the fabricated cutoff wall or on grout, will need to be investigated.

Backfill Preparation (Alternates)

1. In-situ soil, groundwater, borrow soil (may be needed to achieve desired gradation), bentonite, with disposal of excess contaminated slurry.
2. "Washed" in-situ soil, off-site water, borrow soil (some), bentonite, with disposal of excess contaminated slurry.
3. Items 1 or 2, without the need to use borrow soil (i.e., the in situ soil has an adequate gradation).
4. Borrow soil, off-site water, bentonite, with disposal of excess contaminated slurry and disposal of all excavated soil.

Catastrophic Failure - During Construction

Old buried channels have been encountered within the confines of RMA in the silty or clayey alluvium. Some of the channel materials, as well as layers and seams, are predominantly granular and relatively pervious. It is not unreasonable to suspect that leachates in Basin A' are "perched" in these pervious zones. It is therefore likely that

trenching operations can intercept leachets that are under a greater hydraulic head than the slurry in the trench. If off-site water is used for mixing with slurry or backfill materials, the intercepting of high leachate-bearing pervious soil (i.e., contamination) can be an important consideration.

Catastrophic Failure - Post-Construction

Because of the nature of the backfill (i.e., soil and slurry) and its placement in the trench, it may not be possible to reproduce the in-situ density of the subsoil. As a result, the soil mass adjacent to the trench will be able to "expand" or "creep" laterally with time. The relationship of such movements (especially under the influence of seismic activity) with the stability of nearby structures and earth masses needs to be investigated.

Thin-Wall Grout Screen

A vertical thin-wall grout "strip" can be constructed in subsoil materials by driving or virbrating an H-pile or box-pile section into the ground to a predetermined elevation, then gradually withdrawing the pile while simultaneously filling the void left behind with a grout (see Figure D3a and D3b). A grout-pipe is attached to the inner web-flange corner (H-pile) running the length of the pile, which is used to grout the void-space left behind by the ascending pile section. The grout is a plastic clay-bentonite-cement (usually 1 part cement to 3 parts clay).

To construct the thin-wall screen (see Figures D3b, D3c, and D3d), a group of H-piles with attached grout pipes are driven or vibrated into place side by side in a straight line. When all of the piles

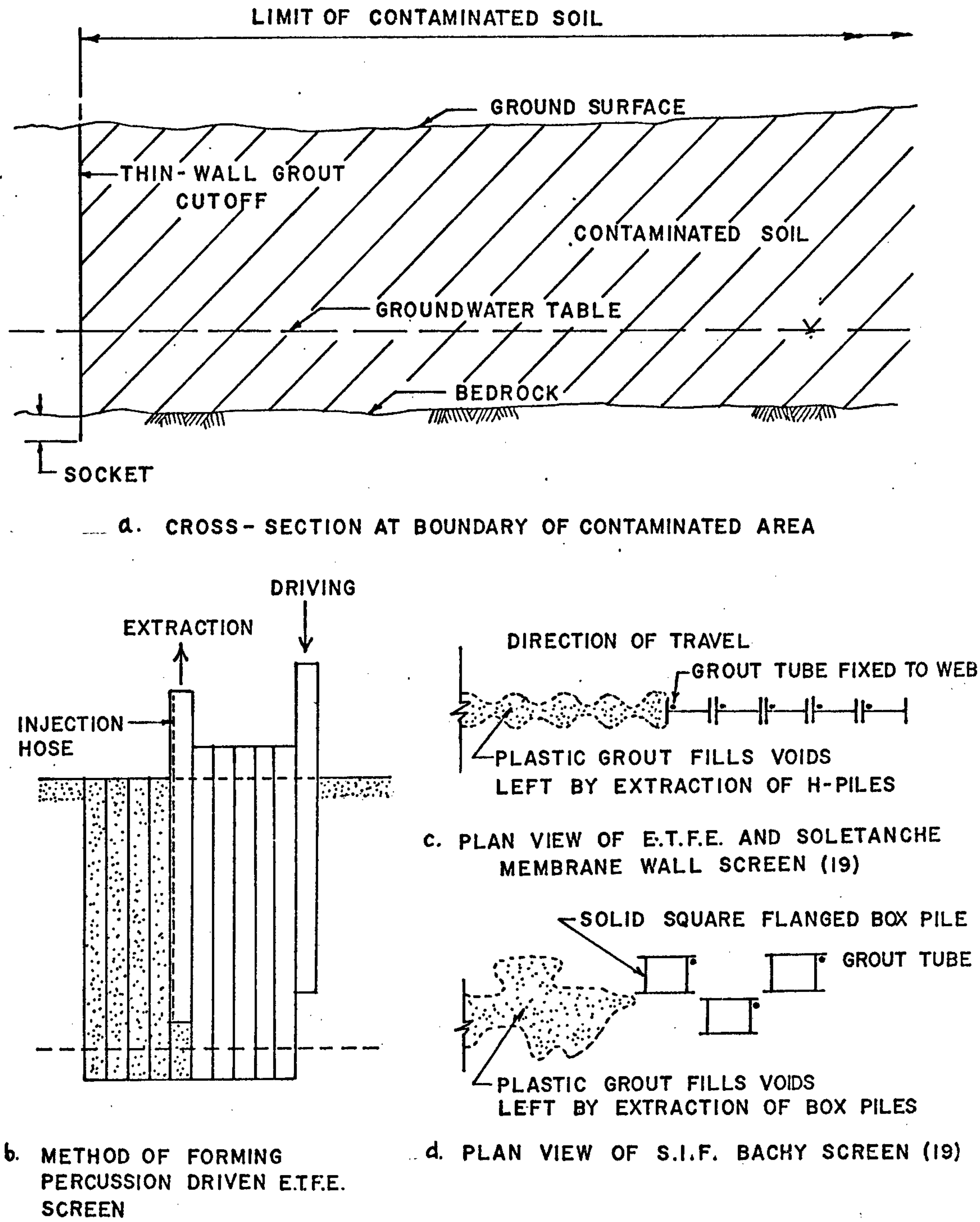


FIGURE D3 : THIN-WALL GROUT CUTOFF

have reached a relatively impervious bottom, the H-piles are withdrawn one by one (while allowing grout to fill the remaining void) in the original sequence in which they were driven, and then redriven at the far end and the process repeated. The result is a grout screen of low permeability ($10^{-6} < k < 10^{-7}$ cm/sec) and low structural strength. The degree of impermeabilization achieved by thin-wall screens is reported to be greater than that achieved by the slurry-trench method; i.e., 10^{-7} as compared to 10^{-5} cm/sec, respectively.[20]

The maximum depth to which thin-wall screens can be installed is reported to be on the order of 50 ft.[19] This limitation is primarily due to difficulties incurred in driving and pile deviation (poor joints, etc.).

Vibrators should be considered for use for installing piles in dense gravels. (Piles may be driven by conventional means for particle sizes up to 50 mm grain-size; however, a vibratory-type pile driver is recommended for particle sizes above 50 mm). Rates of 70 lin ft of screen per day (28-ft depth) have been reported using vibratory means of installation.[19]

The thin-wall method has been reported to be faster and to provide greater accuracy than other comparable cutoff schemes. It is also reported that the thinner wall results in savings in labor, equipment, and slurry materials.[20]

In order to obtain a good seal at the bedrock-cutoff interface, the wall will have to penetrate into the bedrock surface to some suitable distance. Information is not available on whether thin-wall screens can be "socketed" into hard compact surfaces. The efficiency of the bedrock seal, therefore, will also need to be investigated.

Materials Compatibility Studies (See Appendix I)

The thickness of the thin-wall screen can vary from about 2 to 3 in., depending on the method of installation (H-pile, E.T.F.E. and Soletanche screen; box-pile, S.I.F. Bachy screen; E.T.F.E., Soletanche, and S.I.F. Bachy, are thin-wall screen contractors). Because of the relative thinness of the screen, possible deterioration by chemical attack of the grout during or after hardening is an important consideration.

Catastrophic Failure

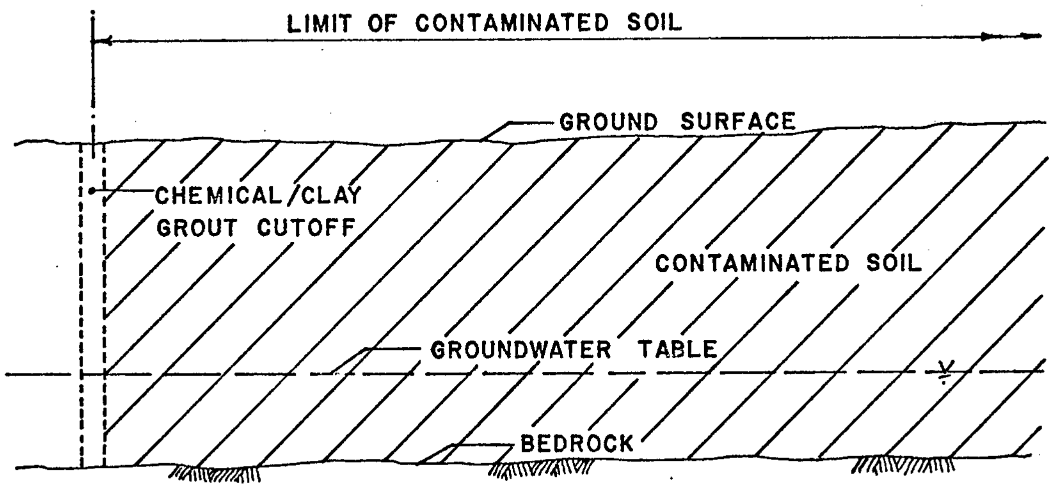
Unbalanced hydrostatic pressures may have some undesirable effect on the thin-wall screen. Because the wall is totally embedded in the soil, lateral translation or yielding of the wall due to unbalanced hydrostatic pressure alone is not anticipated. The likelihood of failure (i.e., cracking etc.), however, needs to be considered. Shear stresses induced in the screen by seismic activity may be significant considering the wall's relative thinness.

Grout Curtain

A structurally nonbearing grout curtain is a vertical, relatively impermeable barrier that is constructed in soil or rock by pressure injection of a gelling or hardening fluid (see Figure D4). The construction process is commonly known as injection or pressure grouting.

Buried grout curtains have the primary function of acting as an impermeable barrier for decreasing or cutting off underground seepage, or for preventing pollution or contamination of groundwater.

Impermeabilization is accomplished by replacing the water in the void spaces between soil grains with a gelling or a hardening fluid substance.



a. CROSS - SECTION AT BOUNDARY OF CONTAMINATED AREA

FIGURE D4 : GROUT- CURTAIN

Grouts are generally classified according to their rheological origin as nongranular Newtonian or as granular Binghamian materials--that is, chemical or cement and/or clay grouts, respectively.

Cement grouts are relatively less expensive than are clay and chemical grouts, and therefore are more widely used.

The following is a tabulation listing some of the currently known grouts that are used for impermeabilization purposes (the list is by no means an exhaustive one):

<u>Bingham suspensions</u>

Aerated mix
Bentonite gel
Clay gel
Clay-cement

<u>Newtonian Solutions</u>

<u>Colloid solutions (gels)</u>

Bentonite gel
Lignochromate
Light carongel
Soft silicagel
Vulcanizable oils
Others (terrainer)

<u>Pure solutions (resins)</u>

Acrylamide

Aminoplastic

Phenoplastic

Chemical grouts are solutions that do not contain suspended solids. They form solids by a controlled chemical catalysis which results in a gel or a precipitate. Cement grouts, on the other hand, contain solids in suspension that may also "gel" or harden.

Groutability or grout penetrability may be defined as the relative ease with which a given soil or rock may be pressure impregnated with a given grout. Groutability is primarily a function of soil particle size, grout pressure, and viscosity. For cement grouts, if the grout particle size is less than a third of the void-space size, the soil can be considered to be groutable with that particular grout. Charts and tabulations on groutability are available[21,22] which relate cement and chemical grouts to soil particle size.

Generally, chemical grouts are applicable for impermeabilizing fine-grain soils and cement and/or clay grouts for clean coarse granular materials. The following is a tabulation of grain-size range and applicable impermeabilization grouts:

Soil Particle-Size Range	Grout
Coarse sands and gravels	Bingham suspensions
Medium to fine sands	Newtonian: colloid solutions (gels)
Silty or clayey sands, silts	Newtonian: pure solutions (resins)

There are three known construction methods for injecting grout in soils: by (a) successive lifts from the bottom of the borehole, (b) grouting through "tubes á manchettes," and (c) simultaneous drilling and grouting. The injection method that is selected for a particular project is based on average soil particle size in a vertical zone, grout type, and injection rate desired.

Grout pipes are strategically placed in order to limit the zone of soil to be treated. An attempt is made to fill as thoroughly as possible (or up to a desired degree) all voids within the boundaries of the volume

of soil to be treated without wasting grout. For a three-lined grouted cutoff, the outside lines will have only one purpose--to create a cofferdam preventing the grouts of the inner line from escaping outside the volume to be treated. The outside lines will be injected with a cement grout, and each hole will only receive a predetermined quantity. The inner row will be grouted to achieve the greatest degree of filling. This treatment involves the use of several grouts of decreasing viscosities.[23] Hole spacing will be smaller for finer grouts (gels or resins) and greater for coarser grouts (e.g., clay and/or cement) because of the application of fine grouts for less pervious soils.[23]

Materials compatibility studies (see Appendix I)

Chemical hardening is based on a chemical reaction; it is therefore possible that the chemical characteristics of the soils, groundwater, or off-site mixing water can have an adverse effect on the reaction of the chemicals in the ground.

Construction Consideration (Injection)

The soil overburden profile in Basin A' consists of silty and/or clayey sands. Layers and pockets consisting of mixtures of other soils are often encountered throughout the strata. In general the overburden is relatively impervious. The selection of grouting materials, determination of soil layers to be grouted, groutability, etc., is dependent on the in-situ subsoil conditions prevailing in Basin A'. The in-situ subsoil conditions are not currently known to the degree that is required for designing a grouting program in Basin A'.

Catastrophic Failure

No stability problems arising from sliding, bearing, seepage, or settlement are envisioned. Distress and failure due to seismic activity need to be investigated.

Appendix E

Estimates of Cost and Time Schedules

Estimates of Cost and Time Schedules*

Approach:
I. Direct Containment

Sub-Approach	Approximate Construction									
	Time, mos.					Cost, millions				
	sheetpile	slurry	thin-wall	grout chemical	grout clay	sheetpile	slurry	thin-wall	grout chemical	grout clay
1. Peripheral Cutoff Containing Basin A' North of 7th Avenue	11	14	14	20	20	3.25	2.33	2.42	1.68	1.62

Estimates of Cost and Time Schedules *

Approach:

II. Indirect Containment

Sub-Approach

	Approximate Construction									
	Time, mos.					Cost, millions				
	sheetpile	slurry	thin-wall	grout chemical	grout clay	sheetpile	slurry	thin-wall	grout chemical	grout clay
a. Peripheral Cutoff 1. Peripheral Cutoff for Containing "Major" Pollution Source Areas	15	18	18	27	27	6.52	4.71	4.88	3.42	3.32
b. Cutoff Impoundment 1. At Channel a_i and a_o	5	5	5	6	6	1.91	1.66	1.68	1.48	1.47
2. At Channel a_o	4	4	4	4	4	1.56	1.49	1.49	1.43	1.43
3. Mid-Basin A'	5	5	5	7	7	2.87	2.56	2.59	2.34	2.32
c. Relocation of Contaminated Soil to Engineered Storage 1. Above Grade	13	14	14	19	19	6.96	5.73	5.85	4.79	4.86
2. Below Grade			14					17.05		

Note:

Estimates of Cost and Time Schedules*

Approach:

III. No Containment

Sub-Approach	Approximate Construction Time, mos.	Approximate Construction Cost, millions
1. Without Surface Treatment	0	0
2. With Surface Treatment	6	2.82

*Note: Estimates do not include groundwater level control costs (pumping, treatment, and disposal of treated effluents)

Appendix F

Estimated Construction Unit Costs

and

Approximate Dimensions, Areas, and Volumes for Pollution Sources

Table F1

Estimated Construction Unit Costs

Item	Unit Costs (installed)	Comment
Sheet-pile	\$6.40/ft^2	
Slurry-trench	\$3.20/ft^2	
Thin-wall	\$3.50/ft^2	
Grout-curtain		
chemical grout	\$25/yd^3	
clay-cement grout (three-line system)	\$0.75/ft^2	
Grout seal (soil-bedrock interface)	\$4.0/ft^2	
Liner		
barrier	\$3.5/yd^2	
revetment	\$4.4/yd^2	Selection (?), compatibility (?)
Borrow	\$2.0/yd^3	Hauling, grading, compaction, etc.
Site preparation	\$1.0/yd^3	Grading, etc.
Concrete	\$25/yd^3	Tremie, etc.

Table F2

Approximate Dimensions, Areas, and Volumes for Pollution Sources

ution ource	Length (feet)	Area (acres/feet^2)	Average Depth of Overburden (feet)	Perimeter (feet)	Volume (yds^3)
aste & Drainage rea	-	16.9/736,200.	16.	4,650.	436,250.
austic Waste asin	-	20.5/893,000.	16.	6,700.	529,170.
rain Field (*)	-	4.0/174,250.	25.	-	161,350.
ime Settling asin	-	3.4/148,100.	25.	1,700.	137,150.
rash Pits	-	2.3/100,200.	25.	-	92,800.
ontaminated aste Burial Pits	-	0.6/27,000.	16.	-	16,000.
asin A	-	104./4,530,240.	32.	1,200.	-
asin A'	-	551./24,000,000.	16.	21,245.	-
asin A' (to 7th Avenue)	-	-	16.	20,000.	-
tility Sewer ine	13,200.	-	-	-	**
ontaminated ewer Line	9,700.	-	-	-	**

* The limits of the drain field is unknown.

** A zone around the contaminated sewer and utility line may have to be excavated and relocated to storage.

Appendix G

Methods to be Studied in More Detail

Methods to be Studied in More Detail

Approach II. Indirect Containment

Sub-Approach IIb2. Cutoff impoundment of polluted groundwater at Channel a_o

Approach III. No Containment

Sub-Approach III2. With surface treatment

Appendix H

Estimates of Cost and Time Schedules for Determining Detailed Quantitative Feasibility

ESTIMATES OF COST AND TIME SCHEDULES FOR DETERMINING DETAILED QUANTITATIVE FEASIBILITY

APPROACH	SUB-APPROACH		GEOTECHNICAL		SEISMIC		MATERIALS COMPATABILITY[e]		HANDLING HAZARDS[(c) e]		STABILITY		CONTAMINATED SOIL[e]		CONTAMINATED GROUNDWATER[e]		ENVIRONMENTAL (LAKE-RECHARGE, ETC.)		ESTIMATED TOTALS[(d)]	
			TIME, mos.	COST, dollars, 10^3	TIME, mos.	COST, dollars, 10^3	TIME, mos.	COST, dollars, 10^3	TIME, mos.	COST, dollars, 10^3	TIME, mos.	COST, dollars, 10^3	TIME, mos.	COST, dollars, 10^3	TIME, mos.	COST, dollars, 10^3	TIME, mos.	COST, dollars, 10^3	TIME, mos.	COST, dollars, 10^3
II INDIRECT CONTAINMENT	IIb2. CUTOFF IMPOUNDMENT OF POLLUTED GROUNDWATER AT CHANNEL a	SHEETPILE	9	200	4	30	a,e	a,e	1	4	1	5	2	10	2	10	4	30	12	439
		SLURRY TRENCH[b,e]	9	200	4	30	a,e	a,e	1	4	3	15	2	10	2	10	4	30	12	449
		THIN WALL	9	200	4	30	a,e	a,e	1	4	1	5	2	10	2	10	4	30	12	439
		GROUT CURTAIN	11	230	4	30	a,e	a,e	1	4	1	5	2	10	2	10	4	30	12	469
III NO CONTAINMENT	III2 WITH SURFACE TREATMENT		9	200			12	50	1	4			2	10	2	10	4	30	12	304

GENERAL NOTE : STUDIES BETWEEN SUBAPPROACHES MAY DIFFER IN COMPREHENSIVENESS

(a) CONCURRENT (LITERATURE SEARCH, SAMPLING, LABORATORY SET-UP, TESTING, ECT.); TIME ABOUT 12 MO., COST ABOUT $150,000.
(b) MATERIALS COMPATABILITY (ADD $50,000. AND 12 MO.--CONCURRENT--FOR BACKFILL MIX PROCESSING, ETC.)
(c) S.O.P. HAVE BEEN DEVELOPED. REQUIRES FURTHER STUDY ( )
(d) MAXIMUM; DEPENDS ON THE COMPREHENSIVENESS OF MATERIALS COMPATABILITY STUDY
(e) COST AND TIME SCHEDULE IS THE SAME AS FOR RESERVOIR "F" STUDY ; REDUCTIONS ARE POSSIBLE IF PERFORMED BY E.E.L., W.E.S., CONCURRENT WITH RESERVOIR "F" STUDY

Appendix I

Types of Studies Required for a Detailed Quantitative Feasibility Evaluation

TYPES OF STUDIES REQUIRED FOR A DETAILED QUANTITATIVE FEASIBILITY EVALUATION

APPROACH			II INDIRECT CONTAINMENT				III NO CONTAINMENT
SUB-APPROACH			IIb2. CUTOFF IMPOUNDMENT OF POLLUTED GROUNDWATER AT CHANNEL				III2. WITH SURFACE TREATMENT
			SHEETPILE	SLURRY TRENCH	THIN WALL	GROUT CURTAIN	
GEOTECHNICAL	OVERBURDEN	STRATIGRAPHY	*	*	*	*	*
		RELATIVE DENSITY/CONSISTENCY (N)	*	*	*	*	
		INDEX PROPERTIES	*	*	*	*	*
		GRADATION	*	*	*	*	*
		SOIL CLASSIFICATION	*	*	*	*	*
	PERMEABILITY	LABORATORY	*	*	*	*	*
	PERMEABILITY – FIELD	PUMPING	*	*	*	*	*
		LE FRANCH				*	
		MICROMOULINET				*	
	OVERBURDEN	COMPRESSABILITY	*	*	*	*	
		SHEAR STRENGTH		*			
	BEDROCK	SURFICIAL STRATIGRAPHY	*	*	*	*	*
		GEOLOGY	*	*	*	*	*
		CONDITION	*	*	*	*	*
		PERMEABILITY	*	*	*	*	*
		SURFACE EROSIONAL FEATURES	*	*	*	*	*
GEOPHYSICAL AND SEISMIC			*	*	*	*	
MATERIALS COMPATABILITY	CONTAMINATED GROUNDWATER	CONSTRUCTION MATERIALS (SHEETPILING, ETC.)	*	*	*	*	
	GROUT	CHEMICAL			*	*	
		CLAY			*	*	
		CEMENT			*	*	
	SLURRY	CLAY		*			
		BACKFILL		*			
	CONTAMINATED SOIL ABOVE SATURATION ZONE	CONSTRUCTION MATERIALS (SHEETPILING, ETC.)	*	*	*	*	*
	GROUT	CHEMICAL			*	*	
		CLAY			*	*	
		CEMENT			*	*	
	SLURRY	CLAY		*			
		BACKFILL		*			
HANDLING HAZARDS		OVERBURDEN	*	*	*	*	*
		IN-SITU EMERGENCY FACILITIES	*	*	*	*	*
STABILITY		STRUCTURAL (MATERIALS)		*	*	*	
		ROTATIONAL (OVERBURDEN AND/OR NEARBY STRUCTURES)		*			
		BEARING		*			
		SETTLEMENT	*	*	*	*	
		SEEPAGE	*	*	*	*	
CONTAMINATED SOIL (CONCENTRATION VS. DEPTH)			*	*	*	*	*
CONTAM. GROUNWTR. & LEACHTS.		CHEMICAL ANALYSIS	*	*	*	*	*
		CORROSIVENESS	*	*	*	*	
		MOVEMENT	*	*	*	*	*
EVIRONMNT		SOIL EROSION AND TRANSPORT	*	*	*	*	*
		RUNOFF AND INFILTRATION	*	*	*	*	*
		GROUNDWATER RECHARGE	*	*	*	*	*